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CONCEPTUAL DESIGN OF A RADIATION-FREE 800 MeV PROTON LINAC

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Presented is the concept of a 800 MeV proton linear accelerator as a result of long-term research in ion linacs based on alternating-phase focusing (APF) in H-mode structures. Particle motion stability in the medium energy range of 5…100 MeV where the space charge effects are essential and main radiation losses occur, is provided by a combination of modified APF and magnetic focusing. This combined focusing technique can effectively prevent emittance growth and minimize radiation losses.

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INTRODUCTION

Achievements in physics and technology of linear accelerators made it possible to develop and construct a proton linac for the Spallation Neutron Source (SNS) with an output energy of 1 GeV and an average beam power of 1.44 MW [1, 2]. Most of the projects for new ion accelerators as well as modernization and/or upgrade of performing machines are based on the experience gained during SNS development. The modern approach to high-current high-energy linac development can be described in the following way.

An initial part of the linac is an RFQ-based structure that accelerates charged particles from the injection energy of 65…150 keV up to 2…5 MeV. The structure is characterized by a high efficiency in particle capture into resonant acceleration mode, but has a low acceleration rate, a relatively small shunt impedance and, as a result, requires high-level RF power supply. Because of this, the RFQ structures are used for preliminary bunching and pre-acceleration.

An accelerating structure in the form of a cavity loaded with drift tubes (drift tube linac – DTL) with the longitudinal distribution of the RF electric field corresponding to a 2π-wave (Alvarez structure) is used for operation in the medium energy range 5…100 MeV. In DTL structures transverse focusing is provided by strong magnetic guadrupoles and is spatially compatible with RF acceleration. Usually, the DTL section operates at 402.5 MHz frequency.

A chain of electromagnetically connected cavities each of which is an accelerating cell combined into a separate module (coupled cavity linac – CCL) provides acceleration from 100 up to 200 MeV. Electric field distribution along the beam propagation axis corresponds to a π-wave. The operating frequency is doubled and becomes 805 MHz for the CCL section.

Acceleration from 200 MeV up to 1 GeV occurs in a superconducting acceleration structure (superconducting linac – SCL). Each SCL section is a chain of cylindrical corrugated cavities with accelerating cells between adjacent corrugations. Electric field distribution along the longitudinal axis of a SCL-section corresponds to a π-mode. The section operates at the same frequency of 805 MHz.

Research conducted at the SNS showed that effective beam emittance growth mainly occurs in the medium-energy sections where space-charge effects play a considerable role. Subsequently, this leads to an increase in losses in the high-energy sections and, thus, to activation of linac structural units.

Because of this, research on an ion linac featuring minimal particle losses in the medium energy range, as well as the search for new alternatives to the Alvarez structure that show strong focusing of high-current beams is relevant. A linac with such features may be of interest not only as an intermediate part of a more powerful accelerator, but also as an effective tool for neutron physics studies. In particular, such linac may find application in radiative material science, magnetism, physics of condensed matter, activation analysis of chemical and isotopic composition of compounds, isotope generation for medical purposes, neutron therapy treatment of malignant tumor, biology, nuclear physics, etc.

1. PROTON LINAC CHANNEL BASED ON COMBINED FOCUSING

Scientific R&D work on radiation-free ion linacs that are based on H-mode cavities and accelerate charged particle from the injection energy of 75…100 keV to about 100 MeV has been in progress at the Institute of Plasma Electronics and New Acceleration Methods of NSC KIPT. Particle motion stability in the accelerating channels is provided by methods based on accelerating RF field focusing, namely, modified alternating-phase focusing (MAPF) [3] and combined RF focusing (CRFF) [4].

Electrodynamical structures under investigation are interdigital H-mode (IH) cavities for low energy (β<0.1…0.15) [3], whereas for the medium energy range crossbar H-mode (CH) structures with doubled operating frequency are the choice [5]. In the CH-type accelerating structure, each drift tube is connected to the ridge by two stems oriented along the tube diameter and the stem position of two adjacent drift tubes is rotated by 90º.

Figs. 1 and 2 present general designs of the studied acceleration structures.

Known Alvarez-type DTL structures operating at the 2π-mode are almost 30 times large in volume and 3 times longer than H-cavity structures operating at the π-mode (assuming the wavelength is the same).

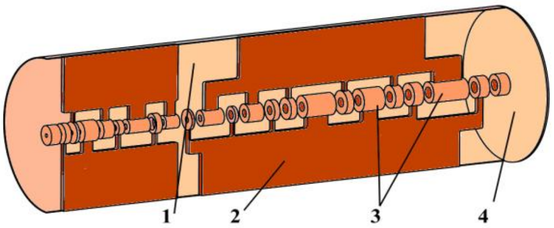


Fig. 1. IH-type cavity featuring APF: 1 – cavity wall; 2 – ridge; 3 – drift tubes; 4 – cavity bottom

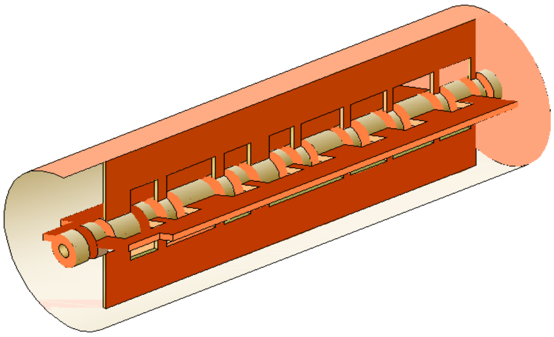


Fig. 2. CH-type accelerating cavity

When developing channels based on MAPF, it was found that there exists a weak damping of phase (longitudinal) oscillation of accelerated particles along the accelerating structure. This, in turn, leads to the acceleration channel lengthening. With the increase in the accelerating period length, the longitudinal component E_z of the RF electric field averaged over the acceleration period is decreased, leading to the acceleration rate reduction. Simultaneously with the weakening of the E_z component, the radial component E_r which is responsible for damping the Coulomb repulsion of beam particles is also decreasing. These effects are significant in the long acceleration section in which the particle velocity is changing by an order of magnitude or more. To keep the acceleration rate and the Coulomb limit for accelerating current high, it is necessary to take special measures to ensure the uniformity of the electric field distribution along the cavity axis by dividing the acceleration channel into several sections or compensating the decrease in electrical field strength by changing the capacitance load along the acceleration path (the drift tube size, the ridge configuration, etc) which complicates the structure. Small size of the drift tubes in the H-mode cavity rules out the use of guadrupole lenses like in the Alvaretz-type structure; as for the use of RF quadrupole focusing, it would result in the accelerating rate lowering, the increase in energy consumption for the accelerating-focusing field generation, and the electrical weakening of the accelerating gaps.

Thus, to increase the focusing strength, avoid the transverse oscillation damping, and keep the accelerating current at high magnitude, some proposals on the combination of APF and additional magnetic focusing have been formulated.

Studies into accelerating-and-focusing channels based on combination of MAPF and additional magnetic focusing have been conducted by means of computer simulation implementing simplified magnetic field along the channel [6 - 8].

There are several ways how to produce a longitudinal magnetic field in accelerating gaps between axisymmetric drift tubes. One of them is to use the tubes made of ferromagnetic material with high saturation induction. The outer shell of the tube is made of copper. The thickness of the shell should exceed that one of the skin-layer. The sequence of the drift tubes with ferromagnetic core and the external yoke system with a solenoid forms a magnetic circuit where magnetic field is concentrated in accelerating gaps between the tubes. Thus, the drift tubes are bifunctional: on the one hand, they serve as electrodes generating electric potential difference to accelerate charged particles and, on the other hand, they serve as magnetic poles of a short magnetic lens to give the additional focusing effect to the charged particle beam [9]. Fig. 3 shows the magnetic induction distribution calculated between two magnetic poles with the use of an internally developed code.

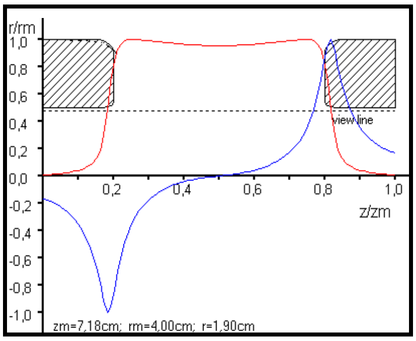


Fig. 3. Magnetic induction distribution between magnetic poles near the inner radius of the drift tubes

In the presence of additional focusing by the magnetic field, it is possible to utilize such MAPF during which a significant phase oscillation damping occurs resulting in the acceleration rate increase on the one hand, and stimulation of the transition to the frequency multiplied by a factor, on the other, which also contributes to the acceleration rate gain and reduces the RF energy losses.

Below presented is the accelerating-and-focusing channel designed for proton acceleration from 0.1 to 85 MeV. The channel consists of 12 accelerating cavities and a buncher (Fig. 4). Main parameters of each section are listed in Table.

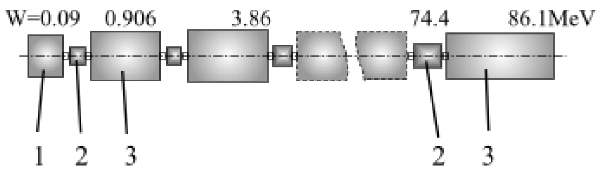


Fig. 4. Accelerating channel: 1 – buncher; 2 – transition lens; 3 – cavity; W – proton energy at the cavity exit

The buncher has 32 RF periods and the same number of magnetic gaps. RF voltage is 1.2…1.5 kV. The buncher delivers the beam to the first section without losses. In the first section which accelerates the proton beam to 0.9 MeV, about 17% of particles are lost (at the injection current of 40 mA). In the next section, the total losses are about ~1.8 10^{-8} A/m at the current of ~35 mA. If the magnetic induction is about 2.3 T on the axis, then losses are ~$1.6 \cdot 10^{-8}$ A/m. When the magnetic induction value goes down to 2.15 T at the current of 33 mA, the linear loss density rises up to ~10^{-7} A/m which is beyond the safety limit for the radiation losses. In the last section, the acceptable level of the loss density is $2.3 \cdot 10^{-9}$ A/m which could be ensured by the magnetic induction value greater than 1.9 T.

Section #	Input energy, MeV	Output energy, MeV	Length, m	Acceleration rate	Operating frequency, MHz	Rms x, π·mm·mrad	Rms y, π·mm·mrad
1	0.09	0.906	1.58	0.51	201.25	0.34	0.33
2	0.906	3.86	2.65	1.02	201.25	0.52	0.53
3	3.86	9.42	2.76	2.01	201.25	0.67	0.7
4	9.42	16.3	2.97	2.3	402.5	0.74	0.73
5	16.3	24.03	3.24	2.38	402.5	0.75	0.79
6	24.03	33.05	3.36	2.68	402.5	0.8	0.81
7	33.05	45.5	4.86	2.54	402.5	0.82	0.83
8	45.5	51.74	1.98	3.2	805	0.91	0.93
9	51.74	58.3	2.08	3.15	805	1.1	1.1
10	58.3	65.7	2.4	3.07	805	1.1	1.1
11	65.7	74.4	2.8	3.1	805	1.1	1.1
12	74.4	86.1	3.05	3.8	805	1.15	1.2

Fig. 5 shows the alteration of the beam rms radius along one of the sections. The yellow line Ra corresponds to the aperture radius.

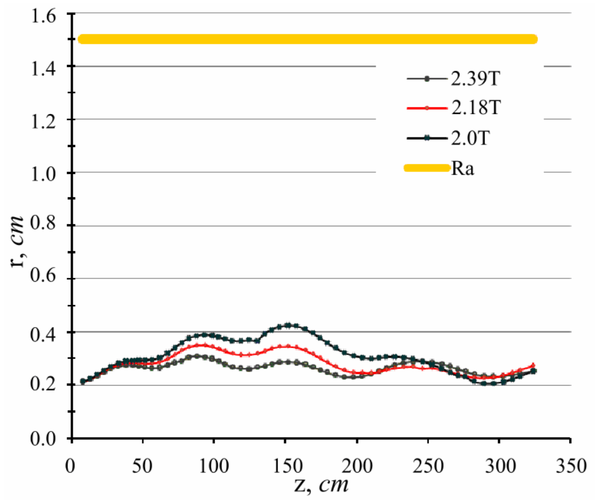


Fig. 5. Change of the beam rms radius along the section #5

This method for particle motion stability in the linac channel provides light ion beam acceleration with the current of 30…35 mA up to 100 MeV. However, the mentioned magnetic field generation procedure is effective only for a short accelerating structure due to the strong magnetic field damping at the structure center. Fig. 6 presents the magnetic induction distribution along the CH-type accelerating structure consisting of 19 accelerating gaps (20 drift tubes, for the general view of the structure see Fig. 2).

There is another way how to generate the additional external magnetic field. It is based on the usage of permanent magnets. It has been proposed to place inside a drift tube a block made of permanent-magnet materials like Samarium-Cobalt or Neodymium-Iron-Boron. These magnetic inserts can be shaped as a hollow cylinder along the entire drift tube length, a combination of three cylindrical elements of different diameters and different magnetization direction (radial or longitudinal), or as a quadrupole.

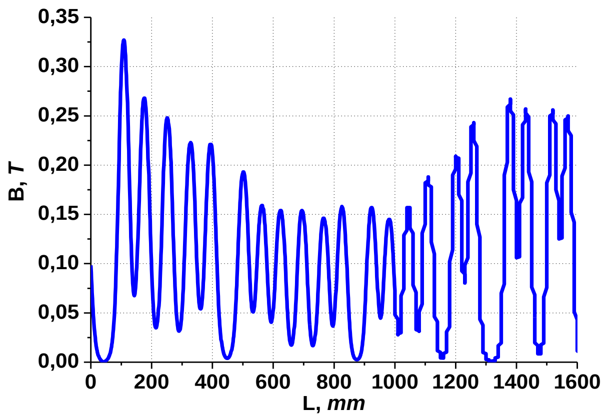
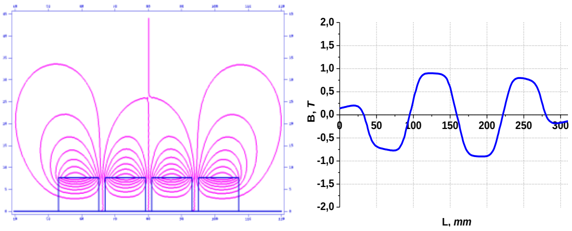


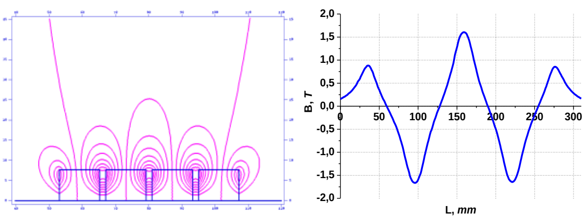
Fig. 6. Magnetic induction flux distribution along the accelerating section axis

Figs. 7,a and 8,a depict magnetic line distribution in radially and longitudinally oriented system of four magnetic units respectively. Axial distribution of magnetic induction is presented in Figs. 7,b and 8,b. It is worth to mention that magnetic insertions in radially and longitudinally oriented systems are of equal volume. As is obvious from the plots, magnetic induction in the system with radially oriented magnetic insertions exceeds magnetic induction in the system with longitudinally oriented magnets by a factor of 1.5.



a *b*

Fig. 7. Magnetic field lines by longitudinally oriented magnets (a); magnetic induction flux distribution along the structure axis (b)



a *b*

Fig. 8. Magnetic field lines by radially oriented magnets (a); magnetic induction flux distribution along the structure axis (b)

Besides, it is worthy of note that the behavior of induction distribution along the axis in the case of radial magnetic orientation differs from the case of longitudinal one. In the former case induction distribution reaches its maximal magnitude in the middle of each gap while in the latter case the maximum is observed in the center of each drift tube. And since the magnetic field is almost zero in the gaps, gap electric strength increases [10]. Numerical simulation of particle dynamics has shown that the magnetic insertions with radially oriented magnetization provide stronger focusing than longitudinally oriented ones. Fig. 9 demonstrates the dependence of output current on input one for three options, namely, longitudinally and radially oriented magnet insertions, and without external magnetic field.

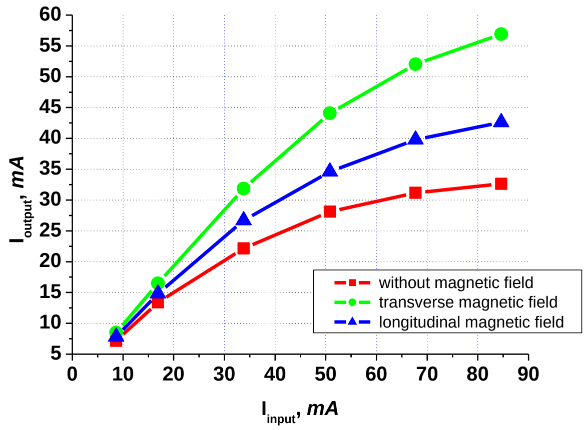


Fig. 9. Dependence of output current on input current

As Fig. 9 suggests, magnetic focusing increases the upper limit of current accelerated.

2. RADIATION-FREE LINAC CONCEPT

As a result of numerous computer simulations of MAPF and combined focusing, the radiation-free proton linac may have the following layout (Fig. 10).

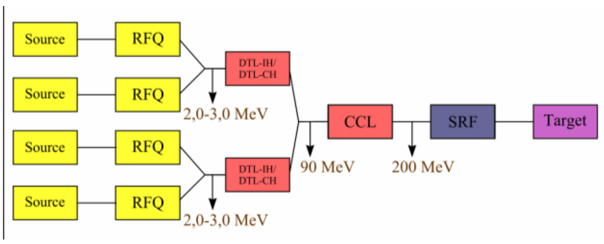


Fig. 10. General layout of the proton linac. Figures present the output proton energy

The initial part consists of four power supply units and four RFQ-sections operating at the frequency of 100…200 MeV. Each RFQ-section is a four-vane structure with modulated electrodes [11] and accelerates a proton beam from 50…75 keV up to 2…5 MeV. On transition from the initial part to the next the operating frequency is doubled. The specific value of the output energy for the RFQ-section is determined by the condition when the phase length of the bunch at the structure end is no more than 40…60° to ensure the phase length is no more than 80…120° at the next section entrance with the operating frequency doubled.

Next are the DTL-IH sections where the combination of APF and magnetic focusing is realized. Each DTL-IH section delivers up to 10…12 MeV of the output energy. Further increase in the output energy reduces the structure efficiency. After the DTL-IH section the operating frequency is doubled again.

DTL-IH section is then followed by two DTL-CH sections in a chain. First DTL-CH section operates on the standing wave, while the second one is of the travelling-wave type. The drift tubes in these sections are similar to the drift tubes in the DTL-IH sections. The output energy at the end of the first DTL-CH section may reach up to 40…50 MeV. As U. Ratzinger, the developer of the CH-type structure, stated such structures are efficient for acceleration to no less than 100 MeV [12]. After this it is desirable to use the travelling-wave structure. To increase the structure efficiency, it is required the backward travelling wave is absent. This can be achieved by removing the backward wave from the structure and feeding it back to the structure entrance by an external circuit. Such technique is used in electron accelerators with recuperation. However, the recuperation technique is not very effective in terms of electron accelerators due to their high operating frequency and, hence, short wave damping length which is about 5 m. The use of recuperation causes the structure effectiveness to increase by no more than two times but at the same time it significantly complicates the realization. Therefore, such technique has not been widely used in the electron accelerators. As for the proton accelerator, it operates at lower frequencies that results in increase in the length of wave damping up to about 100 m. This gives a rise to the effectiveness of the system with recuperation and makes it promising for the proton linac design.

In such structures, it is possible to realize the acceleration process in the case when the backward wave is removed from the accelerating structure and fed back to its entry by directional couplers. When using a $\pi/2$-wave, the upper limit of output energy of the structure increases 4 times. Thus, it is possible to get acceleration up to 200 MeV at the output. If a $\pi/4$-wave is used, the upper limit of the output energy increases another 4 times and can reach 800 MeV.

The proposed acceleration scenario provides the minimum emittance growth, thereby contributing to the radiation losses reduction.

CONCLUSIONS

The design concept of a radiation-free proton linac channel has been presented. In the medium energy range (5…100 MeV) where space charge effects are essential and main radiation losses occur, the particle motion stability is provided by the combination of MAPF and external magnetic focusing based on the usage of permanent magnets.

The IH- and CH-type cavities operating in the standing π-wave mode as well as the travelling wave CH-type cavities serve as the accelerating structures. The channel design proposed provides low emittance growth and meets the requirements for minimum radiation losses. The choice of the structure operating in the travelling wave mode allows for the development of an accelerator for a wide energy range.

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КОНЦЕПЦІЯ РАДІАЦІЙНО ЧИСТОГО ЛІНІЙНОГО ПРИСКОРЮВАЧА ПРОТОНІВ З ЕНЕРГІЄЮ ДО 800 МеВ

С.О. Вдовін, О.В. Мануйленко, М.Г. Шуліка, О.М. Шуліка

Представлена концепція радіаційно чистого лінійного прискорювача протонів з кінцевою енергією до 800 МеВ як результат багаторічних досліджень лінійних прискорювачів іонів на основі Н-резонаторів зі змінно-фазовим фокусуванням. Стійкість руху частинок у діапазоні середніх енергій (5…100 МеВ), де суттєвими є ефекти об'ємного заряду й відбуваються основні радіаційні втрати, забезпечується комбінованим модифікованим змінно-фазовим та магнітним фокусуванням. Така комбінація ефективно запобігає зростанню еміттансу на цьому етапі прискорення та мінімізує радіаційні втрати.