POWER REQUIREMENTS FOR A HIGH-CURRENT PROTON LINAC WITH RADIAL FOCUSING BY AN ELECTRON BEAM

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An estimation for power requirements and efficiency of a linear accelerator with transverse focusing by an electron beam is presented for the following parameters: proton beam current of 100…300 mA, output energy of 3 MeV. The results obtained are compared with the parameters of a demonstration accelerator LEDA (Los-Alamos, USA). It is shown that under conditions of electron beam recuperation at a level of 90%, the efficiency of the proton linac with electron transverse focusing can be essentially higher.

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At present, an initial module of super-powerful proton accelerators (that are either under construction or on a designing stage) is based on the Radio Frequency Quadrupole (RFQ) focusing structure (e.g., see [1]). This type of structure allows the acceleration of the protons from 100 keV up to several MeVs with CW current of about 100 mA and transmission coefficient close to 100%. Such results have been recently demonstrated on the LEDA accelerator with the RFQ structure [2,3].

However, the RFQ-based system has some disadvantages, such as overall complexity, and restriction on the maximal current about of 200 mA. Besides, much of the input power is spent not on a proton acceleration but on a proton focusing (e.g., the accelerating field in LEDA accelerator does not exceed 1.75 MV/m while the RF field intensity on an electrode surfaces is about 33 MV/m [2]). At the same time, it should be noted that cost for the suitable klystrons is about two million US dollars per one megawatt of the RF power [1,4].

In view of the abovementioned remark, this paper deals with further development of an alternative variant for the initial module of a high-current (up to 1 A) proton accelerator with radial focusing by an intense electron beam [5-8]. Our preliminary numerical simulation (made in the approximation of predetermined fields) for the initial accelerator module with the electron beam focusing (EBF) showed the following: a proton beam with an initial energy of 100 keV and current of 0.3 A is accelerated up to 3 MeV; the transmission coefficient in an accelerating mode can reach the value of 99%; the transversal emittance at the linac outlet is 0.40 mm·mrad while the input emittance is 0.32 mm·mrad [6]. At the rates of acceleration comparative to ones in [2], the RF power ohmic losses are less by one order. But the electron beam power is varying from 2 to 10 MW in those calculations. Thus, it is difficult to use such powerful electron beam.

The recuperation process can decrease the input power essentially. For example, the recuperation efficiency of 98% for pulsed electron beam with an energy 100 keV and current 25 A, has been obtained experimentally [9]. As for the CW electron beam (energy 100 keV, current 1 A), the recuperation efficiency has reached 98,6% in experiments [10]. For the recuperation of non-monoenergetic beams in the RF devices, the multistage recuperators are used and their efficiency can be about 95%. In the case of the initial module of accelerator with electron beam focusing, the minimal energy spread of beam electrons can be obtained at the recuperator inlet that makes the recuperation process easier. The acceleration efficiency turns out to be higher for the case of the initial module with electron beam focusing and recuperation than for the LEDA accelerator under similar conditions (see below).

To exclude the radial losses in the subsequent accelerator sections, the transverse mean-square emittance (RMS $\epsilon_\perp$) of the proton beam has to be as less as possible at the outlet of the high-current initial module. In the case of the initial module with EBF, results for $\epsilon_\perp$ (obtained by simulation) are presented in [6,7]. As it has been shown in [6,7], an excessive longitudinal (phase) focusing of protons causes an increase in radial losses and emittance $\epsilon_\perp$ due to Coulomb interaction. So, a longitudinal proton bunch confinement in particular phase region is preferable to the strong longitudinal focusing. In that phase region an equilibrium between the external RF field, Coulomb charge particle interactions, and the magnetic field influence on the electron beam can be optimized. Such equilibrium can be implemented for a proton beam with the current of 300…400 mA and initial energy spread of 0.5% [6,7]. If the proton beam current is 100 mA, the optimal initial energy spread should be about 15% [6].

The interaction between an electron beam and a cavity depends on the initial beam energy. There are three options: (i) the electron beam takes-off the part of the RF field energy; (ii) the electron beam gives the part of its energy to the RF field; (iii) an average energy of the electron beam remains unchanged.

Figs.1 and 2 illustrate an energy spectrum of axis electrons at the outlet of the initial accelerator module. The initial electron energy is 80 keV and 100 keV, respectively. At the cavity outlet the energy spread is about ±5% for 100 keV-energy electrons (see Fig.2). Applying a potential of, say, 90 keV in the recuperator for the electron beam deceleration, one can obtain the recuperation coefficient, K_R , of 85%. As for the electrons of 80 keV initial energy, the energy spread is ±10% and can be decreased by a RF cavity for a beam demodulation. So, Fig.3 shows the energy distribution

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of axis electrons with the initial energy of 80 keV as the electron beam passed over the initial module and the demodulation cavity at the same frequency of 350 MHz.

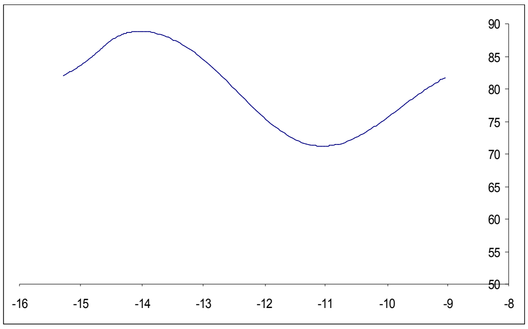

Fig.1

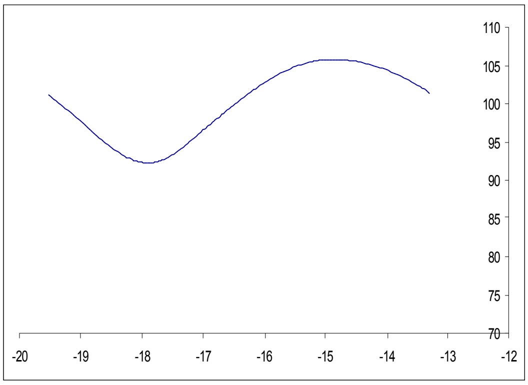

Fig.2

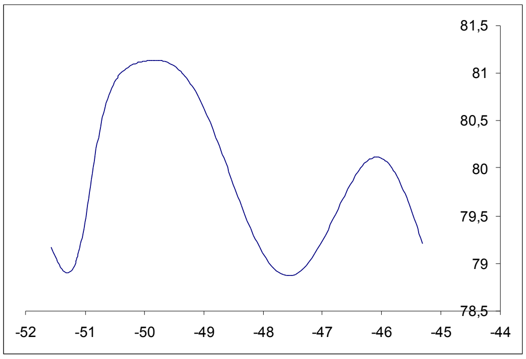

Fig.3

As it follows from Fig.3, the relative energy spread of electrons decreases up to 1.3%. If a potential of 78 keV is applied for the electron beam deceleration in the recuperator, the coefficient of recuperation, K_R, is about 97%. Based on these estimations, let assume K_R=90% for the further calculations.

A Table below presents a comparison of parameters of the accelerator with RFQ focusing (LEDA), and the initial module (IM) with electron beam focusing (EBF). Here, W_p, I_p K_R are the energy and current of a proton beam; W_e, I_e, K_R are the energy, current and recuperation coefficient of an electron beam, correspondingly; $\epsilon_{\perp in}$ and $\epsilon_{\perp out}$ stand for input and output transverse RMS emittances of the proton beam;

Comparison of parameters of the accelerator with RFQ focusing (LEDA), and the initial module (IM) with electron beam focusing (EBF)

Parameters	W_e (keV) I_e (A), K_R %	$\epsilon_{\perp,in}$ // $\epsilon_{\perp,out}$ (mm·mrad)	$P_{kl,E}$, P_{RF}, P_W, P_A, $P_{E,R}$, P_S (MW)	$\eta_{Acc}=P_A/P_{kl,E}$, or $P_A/\Sigma P_{EBF}$,%	K_{Tr}, %
LEDA RFQ, W_p=6.7 MeV, I_p=100 mA	No e-beam	0.22 // 0.31	$P_{kl,E}$=5.6 P_{RF}=3.6 P_W=2.93 P_A=0.67	12%	94
“½” LEDA, W_p=3 MeV, I_p=100 mA	No e-beam	0.22 // <0.31	$P_{kl,E}$=2.49 P_{RF}=1.57 P_W=1.46 P_A=0.30	12%	–
IM with EBF, W_p=3 MeV, I_p=100 мA	(100±0.5) keV, I_e=80 A, 90%	0.32 // 0.88	$P_{E,R}$=0.8 P_A=0.30 P_W=0.23 P_{RF}=0.53 $P_{kl,E}$=0.82 P_S=0.1	16.5%	94.6
IM with EBF, W_p=3 MeV, I_p=100 мA	(100±15) keV, I_e=80 A, 90%	0.32 // 0.40	$P_{E,R}$=0.8 P_A=0.30 P_W=0.23 P_{RF}=0.53 P_S=0.1	17%	98.7
IM with EBF, W_p=3 MeV, I_p=300 мA	(100±0.5) keV, I_e=80 A, 90%	0.32 // 0.64	$P_{E,R}$=0.8 P_A=0.90 P_W=0.23 P_{RF}=1.13 P_S=0.1	44%	99.4

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P_{RF} is the total RF power of three klystrons; P_{kl} is the klystron power consumption at its efficiency η_{kl}=65%; P_W denotes RF power dissipated into the walls; P_A is the accelerated proton beam power; P_{ER} stands for the power consumption of the electron beam taking into account the recuperation; P_S is the power for magnetic field generation; ΣP_{EBF} is the total power for proton acceleration by the initial module with EBF; η_{Acc} is the acceleration efficiency: $\eta_{Acc}=P_A/P_{kl,E}$ for the LEDA, and $\eta_{Acc}=P_A/\Sigma P_{EBF}$ for the module with EBF; K_{Tr} – is the transmission coefficient for the proton beam during the acceleration.

Thus, from the energetic point of view, the initial section of the high-current proton linac with transverse focusing by the electron beam is an acceptable alternative to the conventional RFQ-based accelerator. Under recuperation efficiency of 90%, it is possible to accelerate a proton beam with a current of 300 mA up to energy of 3 MeV with the acceleration efficiency 44% and input RF power 1.13 MW (the latter does not exceed the power of one of three klystrons of the LEDA accelerator [3]).

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ЭНЕРГОЗАТРАТЫ В СИЛЬНОТОЧНОМ ЛИНЕЙНОМ УСКОРИТЕЛЕ ПРОТОНОВ ПРИ РАДИАЛЬНОЙ ФОКУСИРОВКЕ ЭЛЕКТРОННЫМ ПУЧКОМ

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Проведена оценка энергозатрат и КПД в линейном ускорителе с поперечной фокусировкой электронным пучком при токе протонов 100…300 мА, энергии на выходе 3 МэВ. Результаты сопоставлены с параметрами демонстрационного ускорителя LEDA (Лос-Аламос). Показано, что при рекуперации электронного пучка с коэффициентом 90% КПД в первом случае может быть существенно выше, чем во втором.

ЕНЕРГОЗАТРАТИ У СИЛЬНОСТРУМОВОМУ ЛІНІЙНОМУ ПРИСКОРЮВАЧІ ПРОТОНІВ ПРИ РАДІАЛЬНОМУ ФОКУСУВАННІ ЕЛЕКТРОННИМ ПУЧКОМ

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Проведена оцінка енергозатрат та ККД у лінійному прискорювачі з поперечним фокусуванням електронним пучком при струмі протонів 100…300 мА, енергії на виході 3 МеВ. Результати співставлені з параметрами демонстраційного прискорювача LEDA (Лос-Аламос). Показано, що при рекуперації електронного пучка з коефіцієнтом 90%, ККД у першому випадку може бути суттєво вище, ніж у другому.