BEAM TRANSIENT DYNAMICS SIMULATION ON THE BASIS OF COUPLED RESONATORS MODEL IN INJECTOR SECTIONS OF HIGH CURRENT LINACS

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Code on the basis of coupled resonators model was developed for beam transient dynamics simulation in linac injector sections. This code gives possibility to study electron multiflow movement that arises after stopping of some particles in the RF accelerating fields. Motion equations are solved under assumption that field amplitudes in resonators change slow during one oscillation period of RF accelerating field. Beam transient dynamics simulation in linac injector sections was conducted and results are presented in the article.

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INTRODUCTION

Electron linacs with initial beam that is continues during RF period have one peculiarity. If RF electric field amplitude is high enough in initial cells, some fraction of injected particles do not trap into acceleration process. These particles can be decelerated and fall on camera walls or start to move in backward direction. Back-streaming electrons are absorbing by walls or fall onto cathode [1 - 3]. Walls bombardment by electrons can lead to worsen vacuum conditions and, as sequence, to cathode poisoning [2, 3]. Cathode bombardment by electrons change not only cathode emission (see, for example, [4 - 8]), but can lead to its melting [9]. In RF sources back-streaming flow can stimulate an excitation of spurious oscillation [10]. Experimental investigation of processes that are connected with back-streaming electrons is complicated [1]. So, simulation of 3D self-consistent electron dynamics obtained the great importance. Such simulation gives characteristics of back-streaming flows and help to decrease their intensity by optimizing RF field distribution and using additional external influence [1 - 8].

During long time for simulation of electron beam dynamics we are developing method and codes in which the field description is based on the coupled resonators approach [11, 12]. In this paper results that were obtained on the basis of 3D self-consistent code are presented. On the basis of this code we can simulate beam dynamics in the chain of coupled and uncoupled cavities. This code does not take into account quasi-coulomb fields. These fields can slightly change some quantitative characteristics of bunching and accelerating processes. But we think that under injection beam currents that are smaller than several amperes these field cannot to change drastically transient beam dynamics. Taking into account these fields in a model with back-streaming flows can greatly complexify simulation as the number of particles that are moving in the considered region can reach value of several hundred thousands.

1. TRANSIENT DYNAMICS SIMULATION IN INJECTOR SECTIONS OF HIGH CURRENT LINACS

We have made dynamics simulation for three type injectors that consist of:

- two resonators (a prebuncher, a buncher) and an inhomogeneous accelerating section with β_{ph}= 1 (KUT linacs [13], Fig. 1);

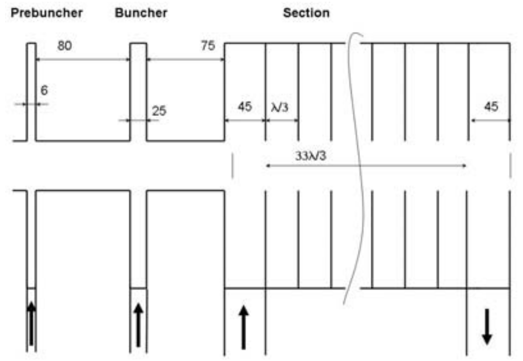

Fig. 1. Linac scheme with a prebuncher, a buncher and an inhomogeneous accelerating section ($\beta_{ph} = 1$)

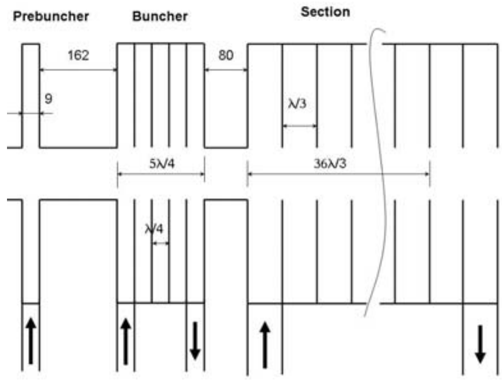

Fig. 2. Linac scheme with a prebuncher, a travelling wave buncher and an inhomogeneous accelerating section (β_{ph}=1)

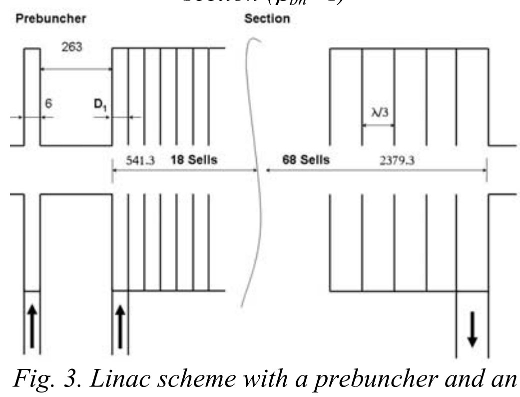

Fig. 3. Linac scheme with a prebuncher and an inhomogeneous accelerating section ($\beta_{ph} = 0.6...1$)

- a prebuncher, a short travelling wave buncher with β_{ph}= 0.75 and an inhomogeneous accelerating section (β_{ph}= 1) (an old SLAC injector, an injector for a Kharkov neutron source [14, 15], Fig. 2);

- a prebuncher and an inhomogeneous accelerating section with $\beta_{ph} = 0.6\ldots1$ (new linac LUE-10 [16], Fig. 3).

1.1. TRANSIENT DYNAMICS IN LINAC WITH TWO RESONATORS AND ACCELERATING SECTION

In this scheme (see Fig. 1) the first resonator and a drift tube realizes klystron bunching, whereas the second resonator accelerates particles for increasing the capture coefficient (ratio of output current to the input one) during acceleration in section with $\beta_{ph}= 1$. The transient process is defined basically by three parameters: settling times in the first resonator ($Q_{prb} = 2500$), in the second one ($Q_{ar}= 10000$) and the filling section time ($t_f \sim 0.5$ μs). Dependences of voltages[1] on the first and second resonators, and also on the resonator of the section output coupler are presented in Fig. 4 (rectangular current pulse with $I = 1.6$ A that is shifted in time on $\Delta t \approx 1$ μs). These dependencies were received without taking into account the back-streaming flow[2] and choosing optimal phasing when the output current reaches maximum value. Note that electric field strength in the second resonator can achieve 300 kV/cm.

Under simulation we suppose that input RF pulses for all devices have the same shape (square-law of a pulse rise with duration $t_{RF} \approx 0.35$ μs and a flat top) and have such steady-state values: $P_{prb}= 200$ W, $P_{ar} = 1.5$ MW, $P_{\sec} = 10$ MW. Injection beam energy equals 20 keV.

RF signal phase changing in prebuncher leads to changing all dependencies except prebuncher voltage as nonbunched beam enters into this resonator.

Taking into account the back-streaming electrons changes beam dynamics. The back-streaming flow arises in the second resonator. But the most significant influence it makes in the first prebunching resonator.

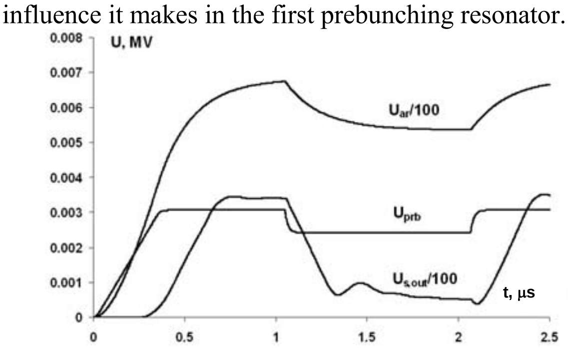

Fig. 4. Dependences of voltages on the resonators without taking into account the back-streaming electrons

First of all we consider the influence of the back-streaming flow on the acceleration characteristics without klystron bunching ($P_{prb}= 0$). From Fig. 5 it follows that the back-streaming flow in the considered geometry decreases both the capture coefficient and acceleration efficiency. It is determined by the fact that the back-streaming flow is modulated on the working frequency and its power is large enough (Fig. 6). In the prebuncher this flow excites field that has no optimal amplitude (voltage is two times larger that the optimal value) and no optimal phase (90° degree shift).

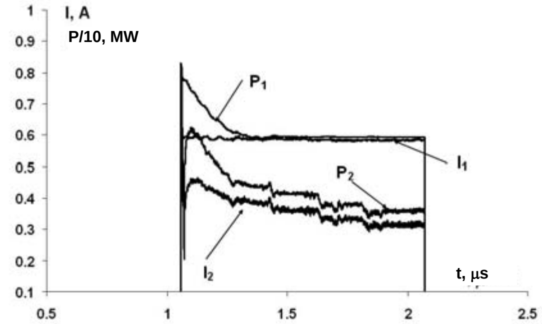

Fig. 5. Time dependence of current and beam power at the section exit under P_{prb}=0: (1) – without the back-streaming flow, (2) – with the back-streaming flow

If $P_{prb} \neq 0$ then electric field in the prebuncher is determined by the superposition of the two fields: field that is exited by the external RF source and one that is exited by the back-streaming flow.

Simulation results show that under constant value of the prebuncher input RF power and different RF signal phase shifts we can excite in the prebuncher RF signal with optimal amplitude or optimal phase. Current value is maximum when field with optimum phase is realized and reaches values up to 1 A under injection current 1.6 A (10% less when field with optimum phase and amplitude is realized). Back-streaming current reaches 10% from output current under such condition. But the transient time is much longer then in the case when back-streaming current equals to zero.

For gaining perspective of decreasing of beam energy spread we conducted simulation of transient processes for different values of delay of current pulse with respect to RF pulse. Results of simulations are presented in Figs. 7, 8.

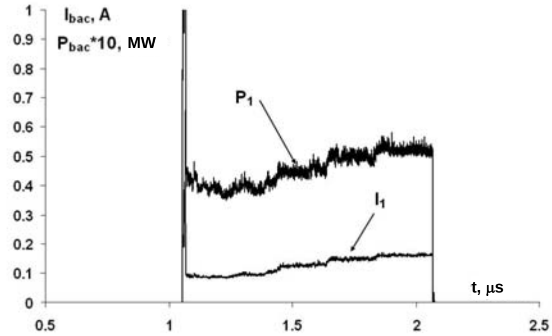

Fig. 6. Time dependence of current and beam power of the back-streaming flow at the prebuncher entrance under P_{prb} =0

It can be seen that for different delay different steady regimes can be realized. These regimes are characterized by different values of current at the section exit. Transition to the new regime occurs under small change of the delay time (near 30 ns). Regime with reduced current has enhanced value of the back-streaming current (see Fig. 8), especially in the transient process.

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[1]Under voltage we understand such value $U_k = \left| \int_0^{d_k} dz\, E_z(z) \right|$ with motion equations $\frac{dp_z}{dt} = -e2\operatorname{Re}\left\{E_z(z)\exp(-i\omega t)\right\}$. Average electric field strength equals $\overline{E}_{z,k} = 2U_k / d_k$.

[2]We have possibility to turn off the influence of the backward electrons

When the injection current is decreased, the described above regime change disappears.

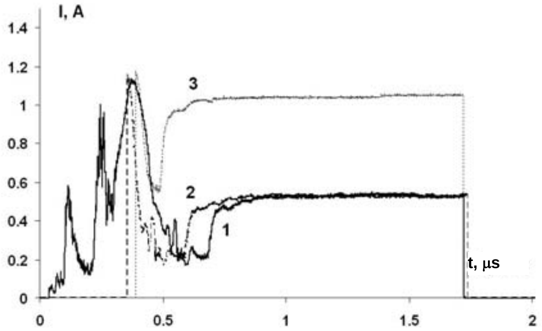

Fig. 7. Time dependence of the current at the section exit under different values of the shift of current pulse with respect to RF pulse: 1 – 0.017 μs; 2 – 0.35 μs; 3 – 0.385 μs

So, taking into account back-streaming flows gives a new result, namely, in injector can be realized two stationary regimes. What regime will be realized is determined by current pulse delay time.

Presented above results obtained for the case of constant injection current. But under presence of the back-streaming flow with high power it is impossible to maintain cathode temperature at the same level and therefore the beam pulse current. This effect will give the additional slow transient process. Uncontrolled injection current changes, from our point of view, is the main difficulty in research the influence of back-streaming flows on grouping and accelerating processes as the injection current depends on the prehistory of accelerator tuning.

In linac KUT-1 at decreasing the time delay less then the threshold one fast disruption of acceleration process take place. After that there is a slow decreasing of current in the cathode circuit[3]. At subsequent increasing the time delay more then the threshold one there is a more faster increasing of current in the cathode circuit then under decreasing the time delay.

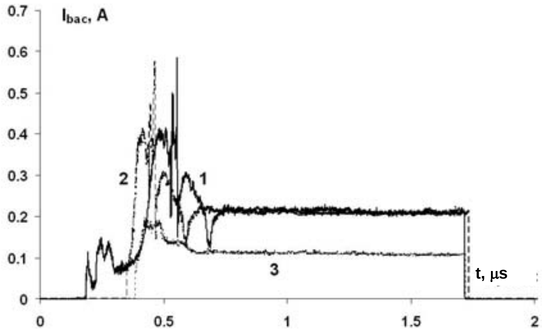

Fig. 8. Time dependence of the back-streaming current at the section entry under different values of the shift of current pulse with respect to RF pulse: 1 – 0.017 μs; 2 – 0.35 μs; 3 – 0.385 μs

1.2. TRANSIENT DYNAMICS IN LINAC WITH PREBUNCHER, TRAWELLING WAVE BUNCHER AND ACCELERATOR SECTION

Described above processes are connected with arising the intense back-streaming flows. In the prebuncher these flows excite RF field with amplitude that is comparative (or even greater) with one that is exited by the external RF source. Such flows arise in the accelerating cavity when electrons are injected in RF field with large amplitude during retarding phase.

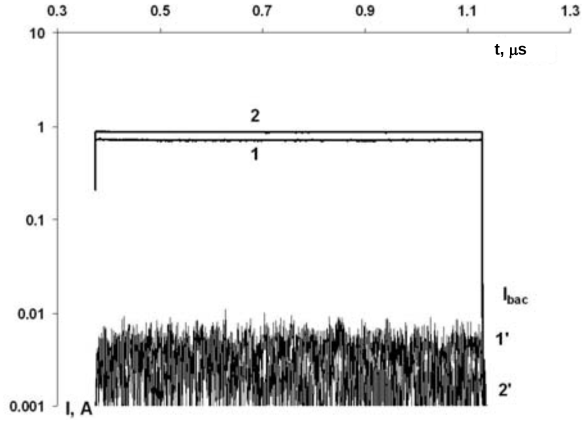

Fig. 9. Time dependence of the current at the section exit and the back-streaming current at the prebuncher entry: 1 – P_{prb}= 0; 2 – P_{prb}= 5 kW

If amplitude of RF field is smaller, the intensity of back-streaming flows will be lower. But in this case the number of particles accelerated in the section with $v_{ph}= c$ will be lower as the injection energy will be smaller. There is possibility to increase the accelerated current by using a buncher with several cavities. In each cavity electric field amplitude will be smaller, but the injection energy will be the same. It has been proposed to use short disk-loaded waveguide with $v_{ph}=const < c$ that work in travelling wave regime (see, for example, [14, 15]).

We have made simulation of 3-D beam dynamic simulation in high current injector (see Fig. 2) that includes the five cavity buncher with $v_{ph}= 0.75\,c$ and inhomogeneous section with $v_{ph}= c$ [15]. It was supposed that input RF pulses have the same shape (square-law of the pulse rise with duration $t_{RF} \approx 0.35$ μsec and the flat top) and have such steady-state values: $P_{prb}= 5$ kW, $P_b= 3$ MW, $P_{sec} = 15$ MW. Injection beam energy equals 120 keV, injection current - 1 A.

Presented in Fig. 9 results show that value of the back-streaming current reduced by an order of magnitude as the capture coefficient became greater (0.7 at $P_{prb}= 0$ and 0.85 at $P_{prb}= 5$ kW; for scheme considered in subsection 2.1…0.2 и 0.66, respectively).

1.3. TRANSIENT DYNAMICS IN LINAC WITH PREBUNCHER AND ACCELERATING SECTION WITH VARIABLE PHASE VELOCITY

Much simplification of the scheme considered in subsection 2.2 can be realized in the case of combining waveguide buncher with $v_{ph}< c$ and accelerating section with $v_{ph}= c$.

We have made simulation of 3-D beam dynamic simulation in high current injector (see Fig. 3) with 18 cells with variable sizes that give elevation of phase velocity from $v_{ph}= 0.6\,c$ to $v_{ph}= c$ [16]. It was supposed that input RF pulses have the same shape (square-law of the pulse rise with duration $t_{RF} \approx 0.35$ μsec and the flat top) and have such steady-state values: $P_{prb}= 1.6$ kW,

[3] Current in the cathode circuit equals difference between emission current and backward current.

P_{sec} = 4.6 MW. Injection beam energy equals 80 keV, injection current 0.44 A.

From Fig. 10 it follows that the value of the back-streaming current reduced again by a factor of 10. The capture coefficient increased, too (0.8 at P_{prb}= 0 and 0.93 at P_{prb}= 1.6 kW).

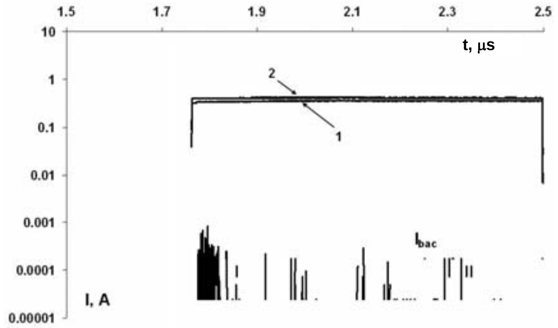

Fig. 10. Time dependence of the current at the section exit and the back-streaming current at the prebuncher entry: 1 – P_{prb}= 0; 2 – P_{prb} = 1.6 kW

SUMMARY

Results of simulations show that electron back-streaming flows can make significant influence on the characteristics of the accelerated beams in linacs. But there are schemes of injectors that give possibility to decrease this influence practically to zero.

REFERENCES

1. M.I. Ayzatskiy, A.M. Dovbnya, V.A. Kushnir, et al. Beam autobunching in the electron linac injector // *Kharkov University Bulletin. Series "Nuclei, Particles, Fields"*. 2002, № 569, № 3(19), p. 69-73.
2. N.E. Rosanov. Electron back-streaming flow in standing wave linacs // *Scientific session MEPhI - 2007. Proc., V.7 Astrophysics and cosmophysics. Modern mathematics problems. Beam physics and accelerator technique.* M., 2007, p. 184-185 (http:// library.mephi.ru/ 934/935/ scientific-sessions? ear=2007& Volume=6).
3. P. Gouard and S. Champeaux, P. Liger, et al. Simulation of an industrial linac (5 MeV, 1 mA, 3 GHz) with magic electromagnetic PIC code // *Proc. of IPAC2010*. 2010, p. 1826-1828.
4. K. Shinto, H. Hama, F. Hinode, et al. Three-dimensional time-domain beam simulation study for a thermionic rf gun // *Proc. of APAC2004.* 2004, p. 297-299.
5. Kai Masuda, Koichi Kusukame, Toshiteru Kii, et al. Particle simulations of a thermionic rf gun with gridded triode structure for reduction of back-bombardment // *Proc. of FEL2005*. 2005, p. 588-591.
6. K. Masuda, K. Kusukame, T. Shiiyama, et al. Design study of rf triode structure for the KU-FEL thermionic rf gun // *Proc. of FEL2006.* 2006, p. 656-659.
7. M. Borland, X. Dong. Simulation of cathode back-bombardment in a 100 MHz thermionic rf gun // *Proc. of LINAC2010*. 2010, p. 944-946.
8. Carl Eichenberger, Dennis Palmer, Sik-Lam Wong, et al. 7.5 MeV high average power linear accelerator system for food irradiation applications // *Proc. of Pulsed Power Conference* 2005 IEEE. 2005, p. 1274-1277.
9. A. Alimov, O. Chubarov, D. Ermakov, et al. Continuous wave RF' gun: computer simulation, design and tuning // *Proc. of EPAC1994*. 1994, p. 778-780.
10. Z. Fang and S. Fukuda. Instability caused by back-streaming electrons in klystron. // *Proc. of APAC2001.* 2001, p. 505-507.
11. M.I. Ayzatskiy. New Mathematical Model of an Infinite Cavity Chain // *Proc. of the EPAC96*. 1996, v. 3, p. 2026-2028.
12. M. Ayzatskiy, V. Mytrochenko. Injector of intense electron beam // *Proc. of LINAC2008*. 2008, p. 431-433.
13. A.N. Dovbnya, M.I. Ayzatskiy, Ye.Z. Biller, et al. Electron-Linac-Based Radiation Facilities of the Ukrainian National Science Center "KIPT" // *Proc. of the PAC97*. 1997, v. 3, p. 3810-3812.
14. General. *The Stanford Two-Mile Accelerator /* Edit. R.B Neal, New York: W.A. Benjamin, 1968.
15. PEI Shi-Lun, CHI Yun-Long, WANG Shu-Hong, et al. Design studies on 100 MeV/100 kW electron linac for NSC KIPT neutron source on the base of subcritical assembly driven by linac // *Proc. of the IPAC2011.* 2011, p. 1075-1077.
16. M.I. Aizatskyi, A.M. Dovbnya, V.F. Ziglo, et al. Accelerating system for an industrial linac // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2012, №4, p. 24-28.

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МОДЕЛИРОВАНИЕ НА ОСНОВЕ МЕТОДА СВЯЗАННЫХ РЕЗОНАТОРОВ НЕСТАЦИОНАРНОЙ ДИНАМИКИ ПУЧКА В ИНЖЕКТОРНЫХ СЕКЦИЯХ СИЛЬНОТОЧНЫХ ЛУЭ

Н.И. Айзацкий, В.А. Кушнир, Е.Ю. Крамаренко, В.В. Митроченко

На основе модели связанных резонаторов разработана программа для моделирования переходных процессов в инжекторных секциях ЛУЭ. Эта программа дает возможность изучать многопотоковое движение электронов, которое возникает в инжекторе после остановки некоторых частиц в СВЧ-ускоряющих полях. Уравнения движения решаются в предположении, что амплитуда поля в резонаторах слабо меняется за период колебаний ускоряющего поля. Представлены результаты моделирования переходных процессов в инжекторных секциях ЛУЭ.

МОДЕЛЮВАННЯ НА ОСНОВІ МЕТОДУ ЗВ'ЯЗАНИХ РЕЗОНАТОРІВ НЕСТАЦІОНАРНОЇ ДИНАМІКИ ПУЧКА В ІНЖЕКТОРНИХ СЕКЦІЯХ ПОТУЖНОСТРУМОВИХ ЛПЕ

М.І. Айзацький, В.А. Кушнір, К.Ю. Крамаренко, В.В. Митроченко

На основі моделі зв'язаних резонаторів розроблена програма для моделювання перехідних процесів в інжекторних секціях ЛПЕ. Ця програма дає можливість вивчати багатопотоковий рух електронів, який виникає в інжекторі після зупинки деяких частинок в НВЧ-прискорюючих полях. Рівняння руху вирішуються в припущенні, що амплітуда поля в резонаторах слабо змінбється за період коливань прискорюючого поля. Представлено результати моделювання перехідних процесів в інжекторних секціях ЛПЕ.