E9-2019-4

A. P. Sumbaev, A. Yu. Barnyakov [1], A. E. Levichev [1]

ON THE LIMITS FOR THE ACCELERATED BEAM CURRENT IN THE **LUE-200** LINAC OF THE **IREN** FACILITY

Presented at the 29th Linear Accelerator Conference LINAC18,
16–21 September 2018, Beijing, China

[1] Budker Institute of Nuclear Physics, Novosibirsk, Russia

Сумбаев А. П., Барняков А. Ю., Левичев А. Е. Е4-2019-4
О предельном токе пучка в линейном ускорителе ЛУЭ-200
установки ИРЕН

Обсуждается подгрузка ускоряющих полей током пучка линейного ускорителя ЛУЭ-200 установки ИРЕН (источник нейтронов Лаборатории нейтронной физики ОИЯИ). Линейный ускоритель электронов ЛУЭ-200 состоит из двух ускоряющих структур с бегущей волной на рабочей частоте 2856 МГц с системой компрессии СВЧ-мощности SLED-типа. Определены предельные токи пучка для различных значений СВЧ-мощности и длительности тока пучка. Результаты расчетов сравниваются с результатами измерений.

Работа выполнена в Лаборатории нейтронной физики им. И. М. Франка ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2019

Sumbaev A. P., Barnyakov A. Yu., Levichev A. E. E4-2019-4
On the Limits for the Accelerated Beam Current in the LUE-200 Linac
of the IREN Facility

The beam current loading of the accelerating fields is discussed for the linear accelerator LUE-200 of the IREN facility (a neutron source at the Frank Laboratory of Neutron Physics, JINR). The LUE-200 electron linac consists of two disk loaded traveling wave accelerating structures with the operating frequency of 2856 MHz and SLED-type power compression system. The limits for the accelerated beam current are defined for different pulse durations of the beam current and RF power. The calculated results are discussed and compared with the measurements.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2019

INTRODUCTION

The IREN facility [1, 2] of the Joint Institute for Nuclear Research (JINR) is the ADS neutron source (accelerator-driven system). It is known that for electron beams with energy more than 20–25 MeV the integral photoneutron yield from the target is directly proportional to the energy of electrons. The beam energy is limited by the beam current loading effect. Therefore, analysis of the properties of the accelerating structure and search for the optimum parameters of the acceleration is a very topical problem for the LUE-200 linac.

Calculations for the beam accelerated in one accelerating section, powered by klystrons of three types, have been carried out: 5045 SLAC (the maximum pulse power of 63 MW), E3730A Toshiba (50 MW), and TH2129 Thomson (20 MW), taking into account the use of the SLED system.

BEAM LOADING EFFECT FOR THE CZ ACCELERATING STRUCTURE

In the stationary regime, the accelerating field of the wave traveling along the z axis of the constant impedance (CZ) structure can be described by the superposition of two equations [3]:

$$E_z\left(z\right) = E_0 e^{-\alpha z} - I_0 R_{\rm sh}\left(1 - e^{-\alpha z}\right). \qquad (1)$$

The first term of the right side of the equation is caused by an external generator field $E_0 = \sqrt{2\alpha R_{\rm sh} P_0}$, where P_0 is the power of the generator; $R_{\rm sh}$ is the shunt impedance of the structure; α is the loss factor in the structure. The second term defines the field induced by an electron beam with an average current of I_0. It is supposed that the beam consists of dot bunches with length much less than that of the wave which follows with frequency of the own working mode of the structure $f_0 = \omega_0/2\pi$.

By means of (1) it is possible to receive additional beam potential which the beam will obtain at the acceleration:

$$U\left(z\right) = \int_0^z E_z(z)dz = (E_0 + I_0 R_{\rm sh})\frac{1 - e^{-\alpha z}}{\alpha} - I_0 R_{\rm sh} z. \qquad (2)$$

From (2) it is clear that there is a beam current $I_{\rm cr}$ at which the average growth of energy in CZ structure of L length will be equal to zero:

$$I_{\rm cr} = \sqrt{\frac{2\alpha P_0}{R_{\rm sh}}}\frac{1-e^{-\alpha L}}{\alpha L-(1-e^{-\alpha L})}. \qquad (3)$$

In the nonstationary regime, changing of the beam potential will be defined by changing of the generator power $P_0(t)$ and of the beam-induced field by the following equation [4]:

$$\Delta U_b(\tau) = -R_{\rm sh} L I_0 \left\{\left(1-\frac{\tau_{0A}}{T_f}\right)\left[1-e^{-\tau/\tau_{a0}}\right]+\frac{\tau}{T_f}\,e^{-\tau/\tau_{a0}}\right\}. \qquad (4)$$

Here τ is the time from the injection start in the accelerating structure of the first bunch ($0 \leqslant \tau \leqslant \tau_b$, where τ_b is the beam current duration); $\tau_{\alpha 0} = 2Q_{\alpha 0}/\omega_0$ is the time constant of the accelerating structure, $Q_{\alpha 0}$ is the quality factor of the structure; $T_f = L/V_{\rm gr}$ is the filling time of the structure, where $V_{\rm gr}$ is the wave group velocity of an accelerating field. The full beam potential will be composed of the potential obtained from the external generator field without a beam and from the field induced by a beam (4). For the case when the beam flies in the accelerating structure already completely filled with the RF power at $\tau \geqslant T_f$, it is possible to write down

$$U(\tau) = U_m + \Delta U_b(\tau), \qquad (5)$$

where $U_m = E_0(1-e^{-\alpha z})/\alpha$. Thus, the beam particles energy spread-out is defined by the beam current and its duration.

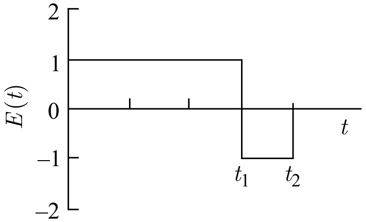

Fig. 1. The RF power signal coming at the input of the SLED system

In case of using the SLED system [4], RF power gained from the generator is nonstationary in time. Let normalized pulse amplitude of an input signal be defined by the dependence shown in Fig. 1. The condition normalizing is the expression for power $P(t) = P_0 E^2(t)$, where P_0 is the power of the generator.

The phase inversion is carried out at the moment of time t_1 and lasts till time t_2. In this case it is possible [5] to write down the wave amplitude $E_{\rm in}$ coming in load and normalized on the amplitude of the generator wave in the following form:

$$E_{\rm in}(t) = \begin{cases} \dfrac{E_{1\rm in}(t)}{E_g}, 0 \leqslant t < t_1 \\ \dfrac{E_{2\rm in}(t)}{E_g}, t_1 \leqslant t \leqslant t_2\,, \\ \dfrac{E_{3\rm in}(t)}{E_g}, t_2 < t \end{cases} \qquad (6)$$

$$\frac{E_{1\text{in}}(t)}{E_g} = \sqrt{\frac{P_{1\text{in}}(t)}{P_0}} = \frac{\beta_{\text{sl}}-1}{\beta_{\text{sl}}+1} - \frac{2\beta_{\text{sl}}}{\beta_{\text{sl}}+1} e^{-t/\tau_{\text{sl}L}},$$

$$\frac{E_{2\text{in}}(t)}{E_g} = \sqrt{\frac{P_{2\text{in}}(t)}{P_0}} = -\frac{\beta_{\text{sl}}-1}{\beta_{\text{sl}}+1} + \frac{2\beta_{\text{sl}}}{\beta_{\text{sl}}+1} e^{-t/\tau_{\text{sl}L}} \left(2e^{t_1/\tau_{\text{sl}L}} - 1\right),$$

$$\frac{E_{3\text{in}}(t)}{E_g} = \sqrt{\frac{P_{3\text{in}}(t)}{P_0}} = \frac{2\beta_{\text{sl}}}{\beta_{\text{sl}}+1} e^{-t/\tau_{\text{sl}L}} \left(2e^{t_1/\tau_{\text{sl}L}} - 2e^{t_2/\tau_{\text{sl}L}} - 1\right),$$

where P_{in} is the power coming in load; β_{sl} is the resonator cavity coupling factor of the SLED system; $\tau_{\text{sl}L} = 2Q_{\text{sl}L}/\omega_0$ is loaded time constant, ω_0 is resonant operating frequency, $Q_{\text{sl}L} = Q_{\text{sl}0}/(1+\beta_{\text{sl}})$ is loaded Q factor, $Q_{\text{sl}0}$ is own Q factor of the resonator. The index "sl" indicates that parameter concerns the resonator of the SLED system.

The power which arrives at the accelerating structure will be defined by the following expression:

$$P_{\text{in}}(t) = P_0 E_{\text{in}}(t)^2. \tag{7}$$

In the accelerating structure, the RF power defined by expression (7) will travel:

$$P_{\text{str}}(z,t) = P_{\text{in}}\left(t - \frac{z}{V_{\text{gr}}}\right) e^{-2\alpha z}, \tag{8}$$

with an accelerating field

$$E_{\text{str}}(z,t) = \sqrt{2\alpha R_{\text{sh}} P_{\text{str}}(z,t)}. \tag{9}$$

Let us consider the period of time from the generator phase inversion t_1 till filling of accelerating structure of the RF power: $t_1 \leqslant t \leqslant t_1 + T_f$, i.e., we will choose for a reference mark $t = t_1$. Then the potential which the beam will receive from the external generator field, in view of (9), will be as follows:

$$U_{\text{str}}(t) = \int_0^L E_{\text{str}}(z,t)\,dz. \tag{10}$$

The potential received by the beam after flight of the accelerating structure at $\tau < T_f$ is

$$U(t) = U_{\text{str}}(t+\Delta t) + \Delta U_b(t). \tag{11}$$

Here it is meant that the RF power impulse can be shifted on time respectively the beam injection on Δt.

For the accelerating structure of LUE-200 (Table 1) in the stationary regime the critical currents received from expression (3) are presented in Fig. 2. One can see a strong dependence of the critical current on power of generator P.

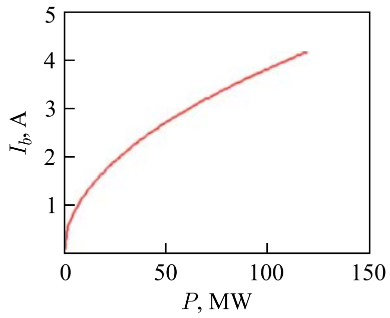

Fig. 2. Critical beam current I_b which can pass through the structure at a zero gradient of a field in the stationary regime

Table 1. Parameters of the LUE-200 accelerating section

Parameter	Value
Operational frequency f_0, MHz	2855.5
Internal cell diameter $2b$, mm	83.75
Iris diameter $2a$, mm	25.9
Iris thickness t, mm	6
Period D, mm	34.99
Operational mode of oscillation θ	$2\pi/3$
Relative phase velocity β_p	1
Relative group velocity β_g	0.021
Section length L, m	2.93
Total number of cells (incl. 2 WTT)	85
Unloaded quality factor Q_0	13 200
Shunt impedance R_{sh}, MOhm/m	51
Time constant $\tau_{0a} = 2Q_0/\omega_0$, μs	1.471
Attenuation (by field) $\alpha = 1/(\tau_{0a}V_{\text{gr}})$, m^{-1}	0.108
Filling time $T_f = L/V_{\text{gr}}$, μs	0.465

Table 2. Resonator cavity parameters of the SLED system

Parameter	Value
Operational frequency, MHz	2855.5
Quality factor Q_{sl0}	86 000
Coupling factor β_{sl}	5

Let us consider the excitation of accelerating structure with the parameters presented in Table 1, powered by a klystron with the SLED system with characteristics specified in Table 2.

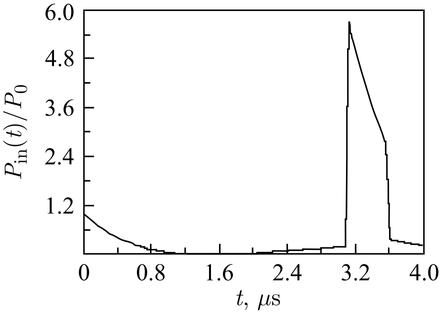

Fig. 3. The envelope of RF power coming to the input of the accelerating structure after the SLED system

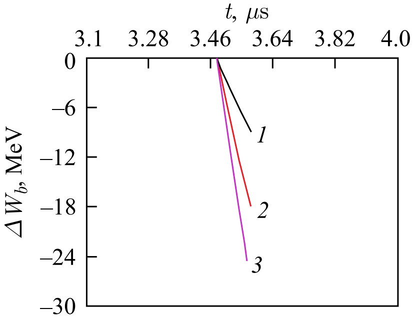

Fig. 4. Losses of beam energy for different beam currents: *1* — $I_b = 1$ A; *2* — $I_b = 2$ A; *3* — $I_b = 3$ A

Let us choose time of phase inversion $t_1 > \tau_{\mathrm{sl}L}$, for example, $t_1 = 3.1$ μs, time $t_2 - t_1 \sim T_f$ or 3.6 μs. Taking into account (6) and (7), the power coming from resonators of the SLED system will look like in Fig. 3.

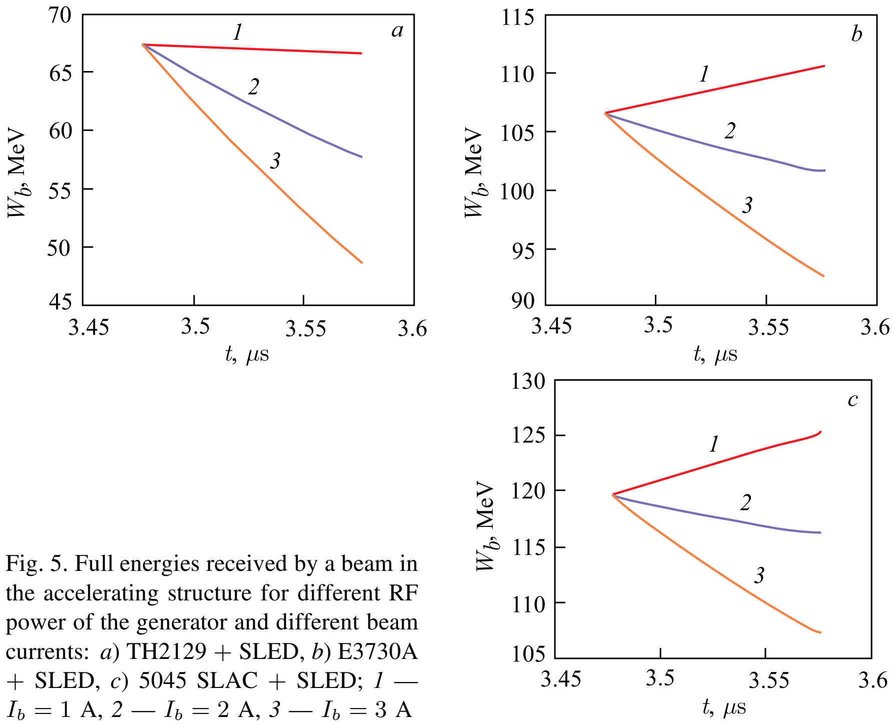

Fig. 5. Full energies received by a beam in the accelerating structure for different RF power of the generator and different beam currents: *a*) TH2129 + SLED, *b*) E3730A + SLED, *c*) 5045 SLAC + SLED; *1* — $I_b = 1$ A, *2* — $I_b = 2$ A, *3* — $I_b = 3$ A

Let us consider a beam with a duration $\tau_b = 0.1$ μs and with a squared shape envelope curve of the beam current. In Fig. 4, the losses of beam energy $\Delta W_b = e\Delta U_b$ for different beam currents are calculated according to (4). The full energy $W_b = eU_b$ received by the beam (11) after flight through the accelerating section, calculated depending on beam duration, is presented in Fig. 5 for different beam currents and different klystrons. Diagrams are constructed on the condition that in the accelerating section all RF power comes after multiplication in the SLED system, and the time of the beam injection is equal to $t_0 = t_1 + T_f - \tau_b$.

From Fig. 5 it follows that for TH2129 klystron + SLED (Fig. 5, a) and for beam currents of 1, 2, and 3 A the average energy and the energy spread are equal to 67, 62, 57 MeV and 1.2, 16, 33%, respectively. For E3730A klystron + SLED (Fig. 5, b), the same values for currents of 1, 2 and 3 A are equal to 108, 104, 99 MeV and 4, 5, 14%, respectively. And for 5045 klystron + SLED (Fig. 5, c), the values are 122, 117, 112 MeV and 5, 3, 11%, respectively, for beam currents of 1, 2 and 3 A.

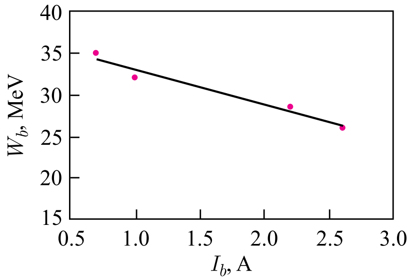

Fig. 6. Position of the maximum of the energy spectrum depending on the current of the beam accelerated in one accelerating section of the LUE-200 linac. Duration of the beam current is $\tau_b = 0.1$ μs

From these estimations it follows that the beam with duration of 0.1 μs loads the accelerating field so, that even at relatively high average energy the beam particles possess substantial energy spread. In Fig. 6, the results of measurements of the beam energy spectra of the LUE-200 accelerator after the first accelerating section are presented [2]. On the vertical axis, the position of maxima of the energy spectrum, and on the abscissa axis, the current of the beam which has passed the accelerating section are specified. The results have been obtained using TH2129 Thomson klystron at pulse power of 17 MW with the SLED system.

It should also be stated that the current results will only qualitatively be coordinated with the results of calculations. Most likely, for the complete analysis of results of measurements it is necessary to consider as well the efficiency of beam bunching in real buncher used on the accelerator. Such calculations are carried out in [6] and prove the current assumption.

CONCLUSIONS

From the presented modeling calculations, it is possible to formulate the following short conclusions:

• At decrease of the RF power reaching the accelerating sections, there is not only energy spectrum "shift" of beam particles to smaller energies but also the spectrum expansion that can result both in disproportionate decrease in the power content of the bunch in a separate cycle and in disproportionate decrease in the beam average power.

• Analytical estimations show that values of critical currents of an electron beam for the accelerating section of the LUE-200 linac are in the range of 3.0–3.5 A which is necessary to consider in search for optimal regimes of acceleration.

• For optimization of acceleration regimes of the LUE-200 linac, it is necessary to test the properties of the SLED system and the efficiency of the operating buncher of the accelerating system.

REFERENCES

1. *Novokhatski A. V. et al.* Linear Accelerator for Intense Resonance Neutron Source (IREN) // Proc. of the 2nd Workshop on JINR Tau-Charm Factory. Dubna, 1994. P. 197.
2. *Belozerov A. V., Becher Yu., Bulycheva Yu. et al.* Physical Startup of the IREN Facility // Part. Nucl., Lett. 2010. V. 7, No. 7(163). P. 923–932.
3. *Wangler T.* Principles of RF Linear Accelerators. New York: John Wiley & Sons, 1998. P. 62–72.
4. *Farkas Z. D., Hogg H. A., Loew G. A., Wilson P. B.* SLED: A Method of Doubling SLAC's Energy // Proc. of the 9th Intern. Conf. on High Energy Accelerators, SLAC, Stanford, CA, USA, May 2–7, 1974. P. 576–586.
5. *Wang J.* RF Properties of Periodic Accelerating Structures for Linear Colliders. SLAC Report-339, July 1989.
6. *Bondarenko T. V., Polozov S. M., Sumbaev A. P.* Numerical Simulation of the Beam Loading Effect at the LUE-200 Accelerator // Part. Nucl., Lett. 2016. V. 13, No. 7(205). P. 1432–1437.

Received on January 18, 2019.

Редактор *Е. И. Крупко*

Подписано в печать 26.02.2019.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,5. Уч.-изд. л. 0,60. Тираж 180 экз. Заказ № 59615.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/