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

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Abstract

The beam current loading of the accelerating fields is discussed for the linear accelerator LUE-200 of the IREN facility (a neutron source at Frank Laboratory of Neutron Physics JINR). The LUE-200 electron linac consists of two disk loaded travelling wave accelerating structure with the operating frequency of 2856 MHz and power compression SLED-type system. The limits by 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.

INTRODUCTION

The IREN facility [1, 2] of the Joint Institute for Nuclear Research (JINR) is the ADS neutron source (**a**ccelerator **d**riving **s**ystem). It is known that for electron beams with energy more than 20-25 MeV the integral photoneutron yield from a target is directly proportional to 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 of the optimum parameters of the acceleration is very actual problem for LUE-200 linac.

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

BEAM LOADING EFFECT FOR THE CZ ACCELERATING STRUCTURE

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

$$E_z(z) = E_0 e^{-\alpha z} - I_0 R_{sh}(1 - e^{-\alpha z}) \tag{1}$$

The first term of the right side of equation is caused by an external generator field: $E_0 = \sqrt{2\alpha R_{sh} P_0}$, where P_0 - power of the generator, R_{sh} - shunt impedance of structure, α - 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 of much less than that of a wave which follow with frequency of own working mode of structure $f_0 = \omega_0/2\pi$.

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

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

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

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

In a 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]:

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

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

$$U(\tau) = U_m + \Delta U_b(\tau), \tag{5}$$

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

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

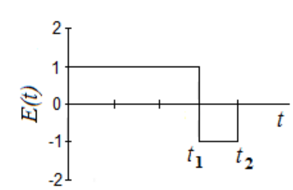

Figure 1: The RF power signal coming at the input of SLED system.

The phase inversion is carried out at the moment of time t_1 and lasts till time t_2. In this case, the wave amplitude

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E_{in} coming in load and normalised on amplitude of the wave of the generator, it is possible [5] to write down in the following form:

$$E_{in}(t) = \begin{cases} \frac{E_{1in}(t)}{E_g}, 0 \le t < t_1 \\ \frac{E_{2in}(t)}{E_g}, t_1 \le t \le t_2 \\ \frac{E_{3in}(t)}{E_g}, t_2 < t \end{cases}, \quad (6)$$

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

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

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

where P_{in} – the power coming in load, β_{sl} - resonator cavity coupling factor of SLED system, $\tau_{slL} = 2Q_{slL}/\omega_0$ – loaded time constant ω_0 – resonant operating frequency, $Q_{slL} = Q_{sl0}/(1+\beta_{sl})$ – loaded Q factor, Q_{sl0} – own Q factor of the resonator. The index "sl" indicates that parameter concerns the resonator of SLED system. The power which arrives at accelerating structure, will be defined by the following expression:

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

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

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

with an accelerating field

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

Let's consider the period of time from the generator phase inversion t_1 till filling of accelerating structure of the RF power: $t_1 \le t \le t_1 + T_f$, i.e. we will choose for a reference mark $t = t_1$. Then the potential which a beam will receive from the external generator field, in view of (9) will be as follows

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

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

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

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

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

Let's 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.

Table 1: Parameters of the LUE-200 Accelerating Section

Operational frequency f_0	2855.5 MHz
Internal cell diameter $2b$	83.75 mm
Iris diameter $2a$	25.9 mm
Iris thickness t	6 mm
Period D	34.99 mm
Operational mode of oscillation θ	$2\pi/3$
Relative phase velocity β_p	1
Relative group velocity β_g	0.021
Section length L	2.93 m
Total number of cells (incl. 2 WTT)	85
Unloaded quality factor Q_0	13200
Shunt impedance R_{sh}	51 MOhm/m
Time constant $\tau_{0a}=2Q_0/\omega_0$	1.471 μs
Attenuation (by field) $\alpha=1/(\tau_{0a}v_{gr})$	0.108 m $^{-1}$
Filling time $T_f=L/v_{gr}$	0.465 μs

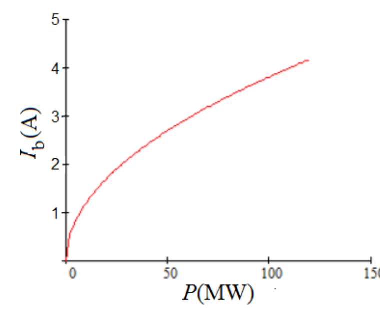

Figure 2: Critical beam current which can pass through structure at a zero gradient of a field in a stationary regime.

Table 2: Resonator Cavity Parameters of SLED System

Operational frequency	2855.5 MHz
Quality factor Q_{sl0}	86000
Coupling factor β_{sl}	5

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

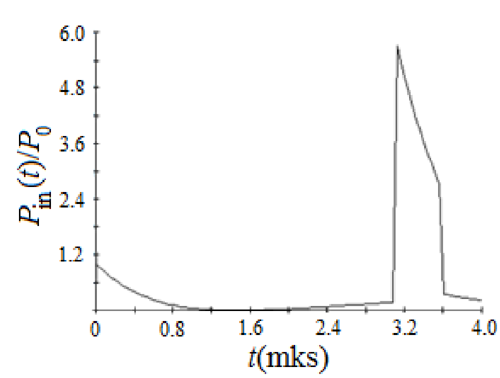

Figure 3: The envelope of RF power coming to input of the accelerating structure after the SLED system.

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Let's consider a beam with a duration of $\tau_b = 0.1$ mks 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).

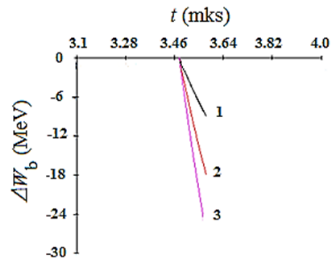

Figure 4: Losses of beam energy for different beam currents: 1 - I_b=1 A, 2 - I_b=2 A, 3 - I_b=3 A.

The full energy $W_b = eU_b$ received by a 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 a 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 $t_0 = t_1 + T_f - \tau_b$.

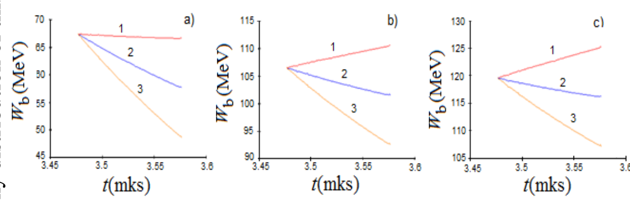

Figure 5: Full energies received by a beam in the accelerating structure for different RF power of the generator and different beam currents: a - TH2129 + SLED, b - E3730A + SLED, c - 5045 SLAC + SLED,
1 – I_b = 1 A, 2 – I_b = 2 A, 3 – I_b = 3 A.

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

From these estimations follows that the beam with duration of 0.1 mks 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 a beam energy spectra of LUE-200 accelerator after the first accelerating section are presented [2]. On the vertical axis the position of maxima of the energy spectrum, on the abscissa axis - the current of the beam which has passed accelerating section are specified. The results have been obtained using TH2129 Thomson klystron at pulse power of 17 MW with SLED system.

It should also be stated that the current results will only qualitatively be co-ordinated 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 which is used on the accelerator. Such calculations are carried out in work [6] and confirm justice of the current assumption.

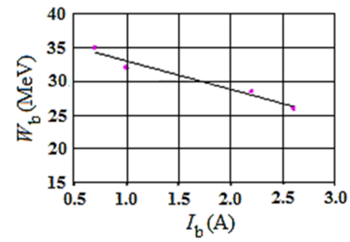

Figure 6: Position of the maximum of the energy spectrum depending on the current of the beam accelerated in one accelerating section of LUE-200 linac. Duration of the beam current is τ_b = 0.1 mks.

CONCLUSION

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

- At decrease of the RF power reaching accelerating sections, there is not simply 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 to disproportionate decrease in the beam average power.
- Analytical estimations show that values of critical currents of an electron beam for the accelerating section of LUE-200 linac are in the range of 3.0 - 3.5 A which is necessary to consider in search of optimal regimes of acceleration.
- For optimisation of acceleration regimes on 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.

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