ELECTRON BEAM STABILITY IN THE ENERGY RECOVERY LINAC FOR THE LITHOGRAPHIC FREE ELECTRON LASER*

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Abstract

According to microelectronic production leaders the lithography based on the free electron laser (FEL) could become the main technology for the elements mass production with scale to 5 nm in the nearest future. One of the main problem is the absence of the working FEL with required parameters. The feasibility study of those FEL based on superconducting energy-recovery linac (ERL) was made in Budker INP. The ERL average current is limited by longitudinal and transverse instabilities, caused by interaction between electron beam and its induced fields in the superconducting cavities. The estimations of the threshold currents and ERL parameters were made.

INTRODUCTION

The feasibility study of high power radiation source for the lithographic applications has been discussed the last decade [1-2]. Using Free Electron Laser (FEL) based on multiturn Energy Recovery Linac (ERL) looks promising for this challenge due to high power radiation and energy efficiency in comparison to another machine types. For the industry application it is necessary to have high power laser radiation and therefore high average electron current and energy in the ERL. For the high energy of the electron beam is the most suitable to use the superconducting radio-frequency system (SRF).

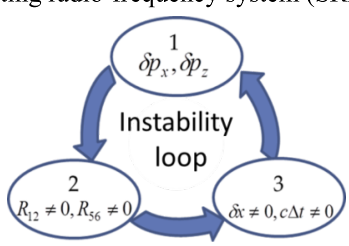

Figure 1: The threshold instability loop.

One of the main problems of the accelerator based on superconducting RF-cavities is the interaction between electron beam and long-living RF-field modes. This phenomenon could cause the degradation of the beam quality and moreover could limit the maximum achievable electron average current. Cavity modes could be spatially divided on transverse and longitudinal by the additional electron momentum obtaining. There is no fundamental difference in mechanics of the instabilities growth between them (Fig. 1): 1 – electron bunch passes through the cavity and gains additional momentum deviation from exited dipole or fundamental RF field modes; 2 – at the magnetic structure momentum deviation transforms to the coordinate, if the appropriate transport matrix elements are nonzero; 3 – electron bunch returns to the cavity and closes the instability loop enhancing dipole and deflecting fundamental RF modes.

ACCELERATOR SCHEME

The using of multiturn ERL scheme reduces the total cost of the facility. The experience with Novosibirsk multiturn ERL (NovoFEL) [3] shows one of the disadvantages the scheme with one accelerating structure. The adjusting of the electron-optical system is complicated by simultaneously pass of accelerating and decelerating beams with different energy spread due to FEL lasing. Therefore it was considered to use the scheme with separated acceleration structure (Fig. 2) [2, 4-5]. The main advantage of such structure is the possibility to independently adjust the arcs optic system for two types of beam. Principle of operation is the following: electrons from injector 1 pass to the pre-linac 2, are accelerated two times in linacs 3, are used in undulator 5, then in decelerating phase follow to the linacs, return energy to thee RF fields and drop to the dump 7. The wavelength of the first harmonic undulator radiation determines the maximum electron energy 800 MeV. For increasing the threshold value and more effective focusing it was considered to have different energy gain at main linacs 100 MeV and 275 MeV while the preliminary linac energy is 40 MeV.

TRANSVERSE STABILITY

All along of unbound arcs optical system main linacs can be considered independently. Therefore due to lower electron energy the lower threshold current is expected in the first main linac. The RF system of the first linac consists of 10 nine cell cavities with accordingly nine horizontal dipole modes. Consequently there are 90 horizontal dipole modes determine the threshold current. To determine the lowest values of the quality it was used the same parameters for the all modes $Q=5\cdot 10^4$, $\rho=100$ *Ohm*.

The threshold current can be estimated using the ultra-relativistic approximation for non-overlapped modes of the accelerating structure. For the multiturn ERL it is given by

$$I_{th} = -2\frac{m_0 c^3}{e}\frac{1}{\omega_m \left(\frac{R_{sh}}{Q}\right)_m Q_m \sum_{k=1}^{2N-1}\sum_{n=k+1}^{2N} M_{12}^{kn}\sin\left(\omega_m\left(T_n - T_k\right)\right)}, \quad (1)$$

where c, m_0, e – speed of light, mass and charge of the electron, ω_m, $R_{sh,m}$, Q_m – frequency, shunt impedance and quality of the cavity dipole mode with number m, T_n is the time of the n-th pass through the cavity.

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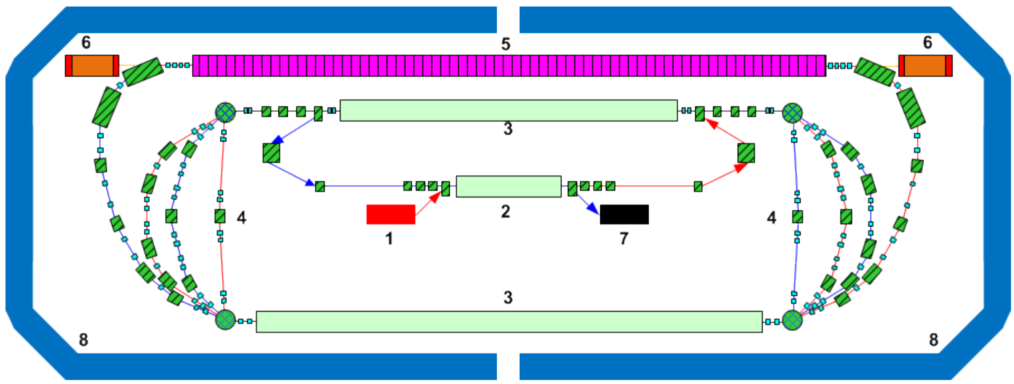

Figure 2: Scheme of ERL: 1 – injector, 2-preliminary linac, 3 – main linacs, 4 – magnetic structure, 5 – undulator, 6 – optical resonator, 7 – dump, 8 – protection walls.

The transport matrix element M_{12}^{kn} between k-th and n-th passes through the cavity depends on betatron function β_n and β_k at this passes

$$M_{12}^{kn} = \gamma_k \sqrt{\frac{\beta_k \beta_n}{\gamma_k \gamma_n}} \sin(\Delta\psi_{nk}),$$

where γ_n, γ_k – relativistic factors and $\Delta\psi_{kn}$ – phase advance. For the beam current optimization, in the first place there was used the technique of reducing the average beam sizes in the cavities by Elegant code [6]. To determine the electron optic of the linac it was used the symmetrical conditions of accelerated and decelerated beams. The second parameter affected on the threshold current is the phase advance. Since it is the periodic function and the arcs optic is independent for the accelerating and decelerating beams it is not necessary to calculate the full accelerator optical structure. After threshold current optimisation founded phase advances would be additional constraints for the focusing structures of the bending arcs. The dependence of the threshold current on the phase advances at the three bending arcs calculated by (1) is shown on the Fig. 3. From this distribution there was selected the area with the optimal threshold current (Fig. 4). The achieved parameters of the accelerator electron optical system were used for simulations in BI code [7]. The results of the simulations are presented on Fig. 5. The minimum threshold current for all modes varies between 90 to 108 *mA* from estimation by (1) to simulations.

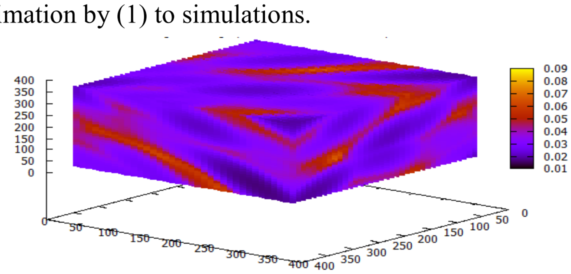

Figure 3: The dependence of threshold current and n phase advances (X,Y,Z axes – phase advance at bending arcs (degrees), colour is the current (A)).

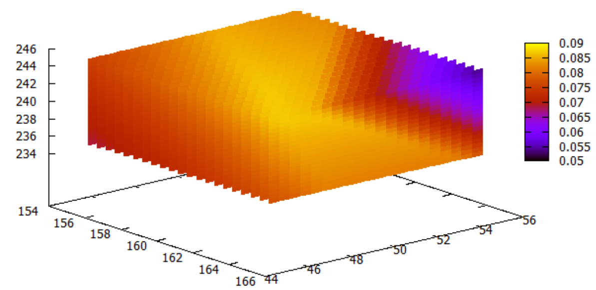

Figure 4: : The dependence of threshold current and phase advances (X,Y,Z axes – phase advance at bending arcs (degrees), colour is the current (A)).

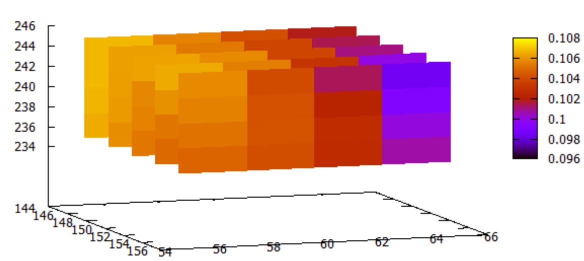

Figure 5: The dependence of threshold current and phase advances (X,Y,Z axes – phase advance at bending arcs (degrees), colour is the current (A)).

LONGITUDINAL STABILITY

To achieve the high power radiation it is necessary to group the electron bunches by motion to undulator (Fig. 2). The nonzero values of the longitudinal dispersion close the instability beam-cavity loop (Fig. 1). The longitudinal stability of multiturn ERL with one acceleration structure was considered previously [8].

Since all cavities have the same fundamental accelerating mode and R_{56} elements of transport matrixes in ultra-relativistic case between cavities in one linac are zero, it possible to use one cavity approximation with appropriate parameters. The beam-cavity interaction can

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be represented as equivalent contour approximation with lumped parameters. Then electron beam and generator currents are presented as current sources. For analysis this system was used perturbation theory of stationary state [9, 10].

To check the theory conclusions there were made simulations used the wake-function of the electron bunch. The comparison of the induced voltage on the cavity calculated by theory and simulated by code is presented on Fig. 6.

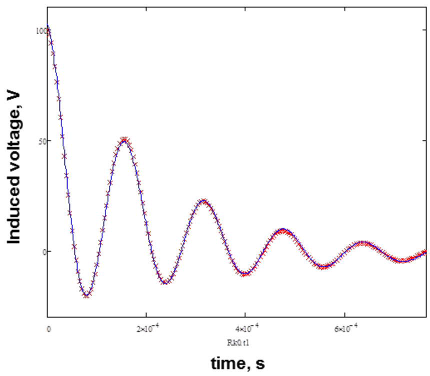

Figure 6: The illustration of the time dependence and induced voltage obtained by simulations (red colour) and by theoretical approximation (blue color).

In case of one undulator it does not necessary to group beam after lasing. Therefore two cases with different R56 were considered: the first is R_{56}=1 *m* for all bending arcs except the undulator arc with R_{56}=2 *m*, the second - R_{56}=1 *m* for all bending arcs before the undulator arc with R_{56}=2 *m* and R_{56}=0 *m* after undulator arc.

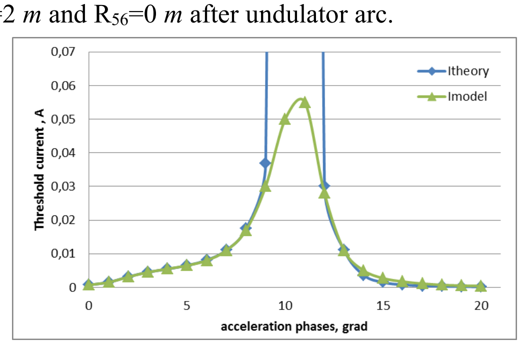

Figure 7: The illustration of the time dependence and induced voltage obtained by simulations (red colour) and by theoretical approximation (blue color).

Calculations show the structure with non-zero longitudinal dispersion at all bending arcs is more stable. The comparison of the theoretical and simulated values of the threshold current for the equal accelerating phases is presented at Fig. 7.

CONCLUSION

There were achieved the permissible quality factor values of the nonsymmetrical dipole modes in the cavities. The stable area of the beta-phase gain at the bending arcs provides the high average current 100 mA.

In case of longitudinal motion were considered two options of the bunch grouping. The nonzero values of longitudinal dispersion parameter at the bending arcs after undulator provide more stable area and higher beam threshold current. There were determined the range of the accelerating phases and cavity detunings necessary for high average current.

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