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 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).

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 \( Q=5 \times 10^4 \), \( \rho=100 \text{ Ohm} \).

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

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

where \( c, m_0, e \) – speed of light, mass and charge of the electron, \( \omega_m, R_{th,m}, Q_m \) – 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.
The transport matrix element $M_{12}^{kn}$ between $k$-th and $n$-th passes through the cavity depends on betatron function $\beta_n$ and $\beta_k$ at this passes

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

where $\gamma_k$, $\gamma_n$ – relativistic factors and $\Delta \psi_{nk}$ – 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 m\(A\) from estimation by (1) to simulations.

### 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...
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).](image)

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 R56=1 m for all bending arcs except the undulator arc with R56=2 m, the second - R56=1 m for all bending arcs before the undulator arc with R56=2 m and R56=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).](image)

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.

ACKNOWLEDGMENT

This work was supported by the Russian Science Foundation (project No. 14-50-00080). The work was done using the infrastructure of the Shared-Use Center "Siberian Synchrotron and Terahertz Radiation Center (SSTRC)" of Budker INP SB RAS.

REFERENCES