NORMAL-CONDUCTING ENERGY RECUPERATOR*

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Abstract

Energy recovery linacs (ERLs) for different applications were discussed intensively last decade. The normal conducting RF ERLs offer the possibility to provide high average currents at relatively low beam energies and long electron bunches. The comparison of normal conducting and superconducting radio frequency (RF) system is described briefly. To illustrate some interesting features of normal conducting ERLs some details of design, operational experience and prospects of the Novosibirsk Free Electron Laser (FEL) ERL are presented.

INTRODUCTION

Accelerator-recuperators or energy-recovering linacs are considered as perspective drivers of future FELs, synchrotron radiation sources, high-energy electron cooling devices, electron-ion colliders. Details of some projects are summarized in a number of reviews [e.g. 1,2].

Many applications of high-energy electron beams change the beam properties such as emittance and energy only slightly. This is true for particle physics experiments, the use of the beam in free electron lasers, electron cooling, etc. Therefore, many large-scale linacs planned for construction last years are conceived as energy recovery linacs [1]. Energy recovery allows to reduce radioactive contamination originated mainly in the beam dump and to use the RF generators of considerably lower power (especially, in case if superconductive cavities are used).

Whereas applications demanding high electron beam energy are heading for superconducting RF linacs due to there high accelerating gradient, normal conducting RF linacs are more suitable for relatively low energy high current applications [3].

In this paper the comparison of normal conducting and superconducting RF is described briefly. To illustrate some particular features of normal conducting ERLs details of design, operational experience and prospects of the Novosibirsk FEL ERL are presented.

RF EFFICIENCY OF ERL

The efficiency of an ERL can be defined as a ratio of reactive beam power to the RF power [4]. Let I is the average beam current, ΔE – energy gain per pass, N – number of passes, E_0 – injection energy, $\rho=R/Q$ – normalized cavity shunt impedance, Q_0 – unloaded quality factor , and e – the charge of electron. Then for the efficiency we get

$$\eta = \frac{I(E_0 + N\cdot\Delta E)}{IE_0 + \dfrac{(\Delta E)^2}{2e\,\rho\,Q_0}}$$

Here we assumed high efficiency of the injector (all RF power is converted to the beam power, since there is no energy recovery there). It is almost true even for non-superconducting injector at high enough currents.

The analysis of this expression shows that at high currents the efficiency tends to E_f/E_0, where $E_f=E_0+N\cdot\Delta E$ is the final beam energy. Characteristic current at which the efficiency saturates is

$$I_c = \frac{(\Delta E)^2}{2e(R/Q)Q_0E_0} = \frac{eP_{RF}}{E_0}$$

which is of the order of 1 A for Novosibirsk ERL and about 1 mA for the JLab FEL/ERL. So increasing average current seems practical for increasing normal conducting ERL efficiency whereas superconducting accelerators are being already operated near “saturation”, when their efficiency does not depend on RF quality.

Increasing number of cavities (and ΔE) at constant current one gets another limit of efficiency $\eta \approx 2NI/I_g$, where I_g is the effective current of the RF generator. I_g is about 0.1A for the Novosibirsk ERL and few mA for superconducting RF systems. As the accelerating voltage is induced both by generator current and beam current the beam current can not significantly exceed the generator current.

STABILITY ISSUES

There are two types of beam instabilities one can expect to occur in an ERL: transverse beam breakup and longitudinal collective instability.

The most important transverse instability is the so-called regenerative beam breakup. It is caused by excitation of the axially asymmetric modes of electromagnetic oscillation inside the linac. The regenerative beam breakup is fully understood now [5,6]. If the linac consists of uncoupled resonators, we may tune the most dangerous TM_{110} mode for each resonator to different resonant frequencies.

Then the threshold current for the transverse beam breakup may be estimated as [7]

$$I_S \approx I_0 \frac{\lambdabar^2}{Q_a L_{eff}\sqrt{\sum_{m=1}^{2N-1}\sum_{n=m+1}^{2N}\dfrac{\beta_m\beta_n}{\gamma_m\gamma_n}}}$$

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where $I_0 = mc^3/e \approx 17\,kA$, Q_a is the quality factor, $ƛ = \lambda/2\pi$, λ is the wavelength corresponding to the resonant frequency of the TM_{110} mode, γ_m is the relativistic factor at the *m*-th pass through the cavity, L_{eff} – is the effective length of the cavity (which is typically almost twice less, than the physical length). This expression shows that it is preferable to use a low-frequency nonsuperconducting RF system (higher λ and lower Q_a) and strong focusing at low energies. It also indicates the limitation for the number of passes.

Estimates show that for the Novosibirsk FEL threshold current of the instability is of the order of 0.1A for the first stage with a single turn and about 20 mA for the second stage with 4 turns. So, up to now we did not observe the instability. For a superconducting accelerator this current falls in some mA range for a single turn machines [6].

We now turn our attention to the longitudinal collective instability. The stability condition derived elsewhere [7]

$$\frac{1}{eI\rho Q} > -\sum_{n=1}^{2N}\sum_{k=1}^{n-1} S_{nk}\sin(\varphi_k - \varphi_n),$$

where φ_n is the phase of the *n*-th pass through the cavity, $S_{nk} = d\varphi_n/dE_k = 2\pi R_{56}(n|k)/(\lambda E_k)$ is the longitudinal sine-like trajectory (proportional to element 56 of the transport matrix), Q is the loaded quality of the cavity. In order to stabilize the instability one must choose longitudinal optics (matrix elements and phases) to make the sum positive. The special case, when all orbits, except the *N*-th, are isochronous, was considered earlier [8]. The stabilization of this instability looks easier to achieve since S_{nk} are the same for all cavities if the beam energy is high enough.

Both instability start currents are inversely proportional to cavity quality factor; therefore normal conducting cavities are preferable for high current applications.

NOVOSIBIRSK ERL

The first stage of the Novosibirsk free electron laser (Fig. 1.), based on the energy-recovery linac generates coherent radiation tunable in the range 120-240 micron as a continuous train of 40-100 ps pulses at the repetition rate of 2.8-11.2 MHz. Maximum average output power is 400 W, the peak power is more than 1 MW [9,10].

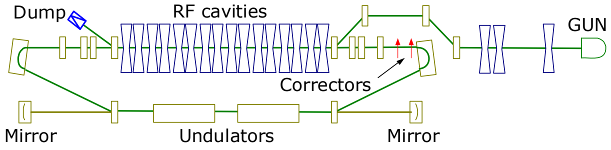

Figure 1: Schematic of the Novosibirsk terahertz free electron laser. Correctors that were used for acceptance measurements are shown.

The first stage contains the full-scale 180-MHz RF system and accelerator structure, but has only one orbit. It differs from the earlier ERL-based FELs in the low frequency nonsuperconducting RF cavities and longer wavelength operation range.

Main parameters of the ERL are summarized in Table 1.

Table 1: Parameters of the Novosibirsk ERL

Beam energy, MeV	12
Average electron current, mA	20
RF frequency, MHz	180.4
Bunch repetition rate, MHz	11.2
Bunch length, ps	100
Normalized emittance, mm·mrad	30
Charge per bunch, nC	2
RF cavities Q factor	$4{\cdot}10^4$

BEAM EMITTANCE MEASUREMENTS

Vital beam parameter for most applications, besides the beam energy, peak and average current, is the beam emittance. Some results of the emittance measurement and optimisation are described below.

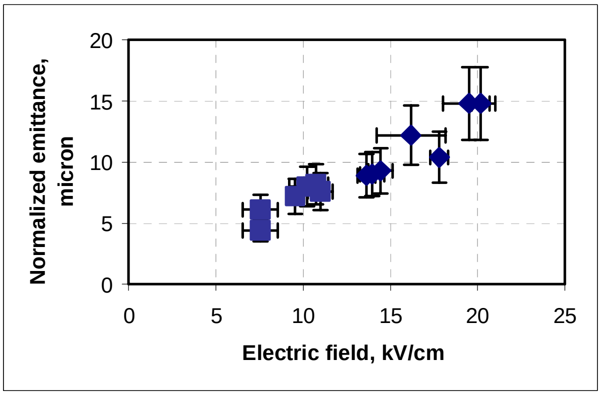

Figure 2: Emittance measurements of the 300kV electron beam. Emittance vs. accelerating field behind the grid is shown.

First, we tried to optimize the beam emittance at the exit of the DC electron gun. We changed the voltage on the first accelerating gap in the gun by shunting the potential divider resistor with a controlled kenotron tube. The measurement technique is discussed in [9]. The results are shown in Fig. 2. Here normalized transverse beam emittance vs. electric field behind the grid is shown. The field before the grid is about 2.5 kV/cm at maximum (limited by modulator performance capabilities). The emittance growth on the grid due to microlensing effect can be estimated as [11] $\varepsilon_{xn} \sim \Delta ERd \Big/ 8\sqrt{3}\sqrt{U\dfrac{mc^2}{e}}$, where $\varDelta E$ is the field jump on the grid, R – cathode diameter, d – grid slit size, U – grid voltage, m, c, e – fundamental constants. Substituting our parameters we get $\delta\varepsilon_{xn}$~1μm·$\varDelta E$ [kV/cm], which is in good agreement with the measurements. Reducing $\varDelta E$ further seems practical to improve beam emittance, but the pay for it is somewhat reduced beam current and stronger space charge effects in longitudinal motion.

Second, emittance measurements of the 1.7 MeV beam in the injector after the first bending magnet were carried out. The dependence of the emittance on bunching cavity voltage amplitude is shown in Fig. 3.

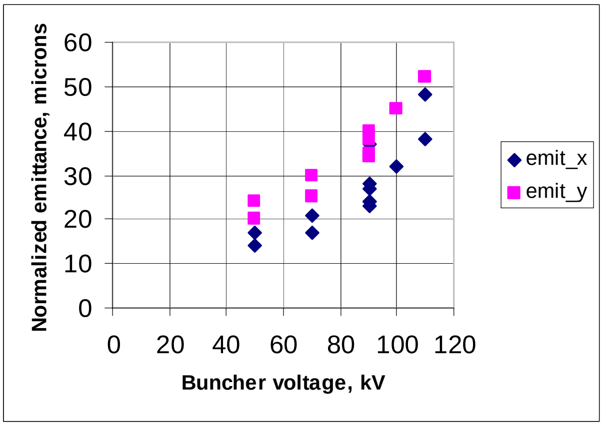

Figure 3: Emittance of the 1.7 MeV beam in injector. Emittance vs. buncher amplitude is shown.

The emittance growth with the bunching is explained by space-charge effects which are intensified in a shorter beam. Estimations of the emittance growth in a free space of length *L* give [12] $\varepsilon_{xn} \sim 0.2 I_{\max} L / [(\beta\gamma)^3 I_0]$, where I_{max} is the beam peak current, I_0=17 kA, β, γ - relativistic parameters. For L=1m, I_{max}=5A we get $\delta\varepsilon_{xn}$~50 µm. Since this emittance growth is not irreversible [12], tuning of the optics can reduce it. Different measurements at the same bunching cavity voltage were made with different optics and points scattering shows the effect of optics tuning.

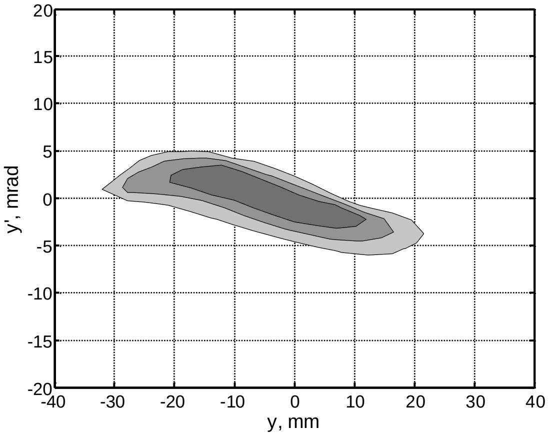

Figure 4: Acceptance measurements of deceleration channel. Contour lines of the normalized dump current. (*y,y'*) plane. Levels are 0.184, 0.5, and 0.816.

Third, acceptance measurements of the decelerating channel were carried out. The accelerator acceptance is measured by a pair of nearby correctors. Correctors vary the beam coordinate and angle, and the current from a Faraday cup in the beam dump is measured. As an example, the results of acceptance measurements in vertical (*y,y')* phase plane are shown in Fig. 4.

The area inside the middle contour line is the channel acceptance (~57 µm in this example, not normalized). Other two contours allow to estimate the beam emittance.

SECOND STAGE OF THE ERL

The design and manufacturing of the full-scale four-turn ERL is underway. An artistic view of the machine is shown in Fig. 5. The existing orbit with the terahertz FEL lies in the vertical plane. The new four turns are in the horizontal one. One FEL is installed at the fourth orbit (40 MeV energy), and the second one at the bypass of the second orbit (20 MeV energy).

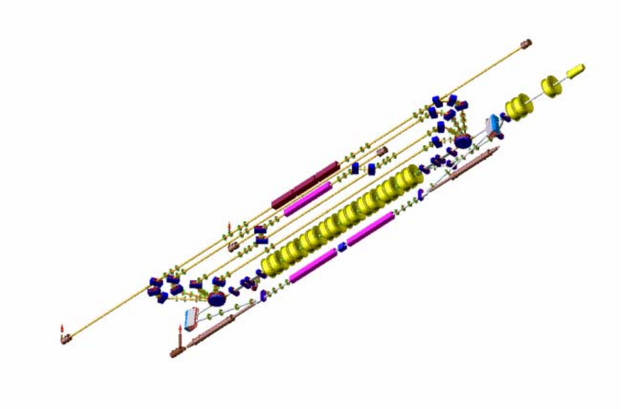

Figure 5: The second stage of the Novosibirsk high power FEL (bottom view).

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