Study on Recirculating Beam Transport and RF Instability for the Energy-recovery Experiment at JAERI FEL

Ryoichi HAJIMA, Masaru SAWAMURA, Ryoji NAGAI, Nobuhiro KIKUZAWA, Nobuyuki NISHIMORI, Toshiyuki SHIZUMA, Eisuke J. MINEHARA
Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki 319–1195 Japan

Abstract

For increasing the average power of JAERI-FEL, we plan to install a recirculating beam transport for energy-recovery operation in the superconducting cells. The present study shows that a beam transport consisting of two triple-bend arcs is suited to the energy-recovery experiment. It is also found that RF instability is not a critical issue in the experiment.

1 Introduction

Stable lasing over 0.1kW in average power between 20–30 μm has been obtained at JAERI-FEL [1][2]. For the further increasing of the power, we plan to make an energy-recovery experiment, where the electron beam used FEL interaction is recirculated and reinjected into the superconducting cells at decelerating RF phase so that the electron beam power can be transformed into RF power [3]. If the energy recovery works efficiently, it is possible to accelerate electron beam of the higher average current without the reinforcement of RF equipment. The enlargement of the average power of FEL output is expected as well. The lattice design of recirculating beam transport for the energy-recovery experiment is described in the present study. We also discuss RF instability in the superconducting cells, which might degrade the energy recovery.

2 Design of the recirculating beam transport

The electron beam should be transported without loss during the recirculation and reinjected into the accelerator cells at the appropriate phase to perform the energy recovery efficiently. The energy acceptance and isochronicity are, therefore, the matters of concern in the design of beam transport for energy recovery. According to the notation of a computer code TRANSPORT [4], the condition for achromaticity in the bending plane is $R_{16} = R_{26} = 0$, and an isochronous arc is obtained if $R_{56} = 0$. Besides the above conditions of the first-order transfer matrix, we take three second-order terms into consideration, T_{166}, T_{266} and T_{566}, which are potential source of beam loss and phase error in the recirculation arc.

One of the sophisticated design of isochronous recirculation is MIT/Bates-type, which was invented for energy doubling in MIT/Bates linac [7]. The same configuration is adopted in Jefferson FEL for their recirculating beam line, where the energy recovery was demonstrated recently [8]. The Bates arc has several excellent features : achromaticity and isochronicity are guaranteed by geometrical design such as bending radius, bending angle, edge rotation of each magnet. The dominant second-order aberrations can be corrected with curvature on the magnet edge. Recirculating path-length is adjustable with small horizontal steering before and after the π-bend.

In spite of the above advantage of Bates-type arc, we decided to chose alternative arc with three 60-degree bends. This is because the footprint of Bates-type arc is hard to fit to the accelerator room and needs more capital cost than the triple-bend configuration which is natural extension of the existing 180-degree arc as shown in figure 1 and 2.

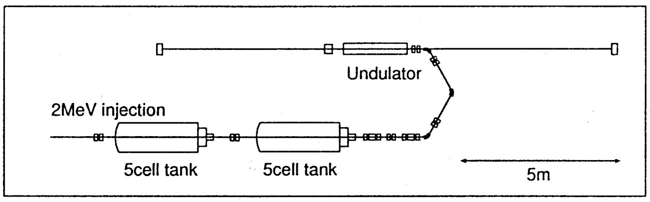

Fig. 1 The layout of JAERI-FEL accelerator room (July 1999).

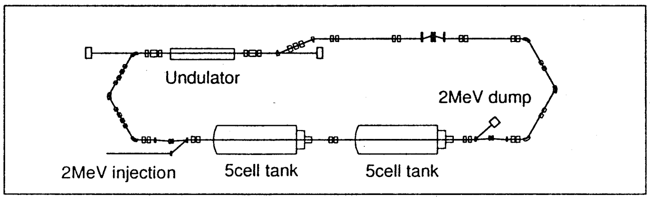

Fig. 2 The layout of JAERI-FEL accelerator room for the energy-recovery experiment.

It is known that the arc consisting of three bending magnets is the minimum configuration for isochronous lattice [9]. The existing 180-degree arc of JAERI-FEL can be isochronous with keeping achromaticity, if we set position and strength of quadrupole magnets at appropriate values. We decided to construct the recirculation transport by adding another triple-bend arc to the beam line. The lattice design of the entire recirculating transport has been determined by a computer code TRANSPORT.

The amount of energy spread caused by FEL interaction is estimated numerically by TDA-3D [10] and the energy spread which contains 99% of electrons in the bunch is found to be ±2.4% with parameters listed in table 1. The obtained energy spread is comparable to the well-known simple estimation : $1/N_w$.

In the present design of arc, the horizontal betatron function and the horizontal dispersion are $\beta_x = 3m$ and $\eta_x = 0.6m$ at the focusing quadrupole in the second arc. The bore radius of 35mm is large enough to accept the electron beam having energy spread of ±2.4%.

Table 1
FEL parameters for the design study

electron beam	
energy	15MeV
peak current	15A
rms energy spread	0.5%
normalized rms emittance	30 π mm-mrad
undulator	
undulator parameter	0.7
undulator pitch	3.3cm
number of period	52
optical cavity	
Rayleigh length	1.04 m
out-couple / total-loss	4.5% / 6.8%

Three dominant second-order aberration terms in the reinjection arc, T_{166}, T_{266} and T_{566}, are $T_{166} = -0.27$m, $T_{266} = -1.6$rad and $T_{566} = -3.6$m, if no sextupole correction is applied. These aberrations cause beam current loss and phase error along the recirculation and make the accelerator unstable. To compensate these aberrations, two families of sextupole magnets are installed at the reinjection arc. These second-order aberrations can be completely corrected by sextupoles.

Injection into the recirculation arc is established by a chicane consisting of four rectangular magnets, where 2MeV injection beam is deflected by 22.5 degree. A similar chicane is installed after the accelerator tank for 2MeV beam dump. Another chicane is inserted at the straight section before the undulator to control the recirculation path-length. Momentum compaction introduced by these chicanes is small and easily canceled at the arcs.

Beam matching along the recirculation transport is also checked using TRANSPORT. It is confirmed that the electron beam can be transported with moderate transverse beam size. Figure 3 shows calculated betatron and dispersion function along the recirculation. The betatron function is kept small in the second arc not to degrade the energy acceptance.

3 RF Instability

The energy flow in the accelerating cavity can be represented by the following equation,

$$\frac{d\tilde{V}_c}{dt} + \frac{\omega_0}{2Q_L}\left(1 - i\tan\Psi\right)\tilde{V}_c = \frac{\omega_0 R_L}{2Q_L}\left(\tilde{I}_g - \tilde{I}_b\right) \quad , \quad (1)$$

where $\tilde{V}_c$, $\tilde{I}_g$ and $\tilde{I}_b$ are the slowly varying complex amplitude of cavity voltage, generator and beam current. Tuning angle Ψ is defined as $\tan\Psi = -2Q_L(\omega - \omega_0)/\omega_0$. In the energy-recovery mode, the beam current is the vector sum of the accelerating and decelerating beams: $\tilde{I}_b = \tilde{I}_1 + \tilde{I}_2$. The decelerating beam is assumed to be perturbed both in amplitude and phase due to the cavity voltage error

$$\tilde{I}_2 = I_0\left[1 + \mu(\varepsilon)\right]\exp(i\left[\Psi_2 + \phi_2(t)\right]) \quad , \quad (2)$$

where $\mu(\varepsilon)$ is beam loss in the recirculation as a function of beam energy error, Ψ_2 is steady-state phase and $\phi_2(t)$ is the phase shift form steady state.

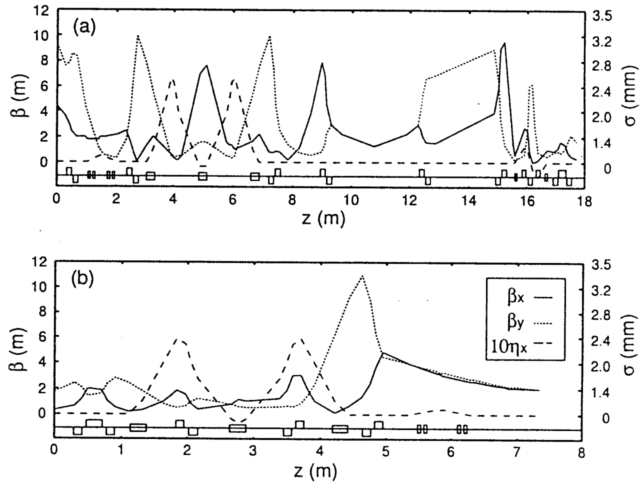

Fig. 3 Betatron function and dispersion function during the designed recirculation: (a) from the accelerator to the undulator and (b) from the undulator to the accelerator.

The equation shows that the perturbation of amplitude or phase in the recirculating beam results in the deviation of cavity voltage from the steady state. Under certain conditions, this perturbation of the cavity voltage grows rapidly and makes acceleration fail. This instability was observed at the energy-recovery experiment of LANL-FEL [11].

In this section, RF instability in our energy-recovery is investigated numerically by solving Eq.(1) with parameters in table 2. The validity of the numerical routines has been checked with the linear analysis [5].

Table 2
RF system parameters for the design study

cavity	
loaded Q	10^6
loaded shunt impedance	$10^9\Omega$
coupling (β)	1000
electron beam	
injection energy	2MeV
final energy	15MeV
average current	6mA $\rightarrow$ 50mA
beam loss parameters	
aperture radius	30mm
η_x	0.6m
$4\sigma_x$	6.9mm
feedback loop	
gain	10
roll-off frequency	300kHz

Equation (1) and (2) show that the instability is caused by either phase shift or beam loss of decelerating beam. The instability is, then, called as phase instability and beam-loss instability, respectively. Even if the recirculating transport is designed as isochronous, error of quadrupole field may introduce residual momentum compaction along the recirculation and the phase instability may occur. The phase shift of the decelerating beam is given by

$$\phi_2(t) = \frac{R_{56}\omega\varepsilon}{cE_b} \ , \qquad (3)$$

where R_{56} is momentum compaction factor along the recirculation, E_b is the designed beam-energy.

The beam loss due to the energy error is modeled by a nonlinear function [6]

$$\mu(\epsilon) = \frac{1}{2}\left[\mathrm{erf}\left(\frac{\delta-\alpha-\epsilon}{\sigma\sqrt{2}}\right) + \mathrm{erf}\left(\frac{\delta+\alpha+\epsilon}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{\delta-\alpha}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{\delta+\alpha}{\sigma\sqrt{2}}\right)\right] \ , \qquad (4)$$

where σ is transverse beam size, δ is aperture radius of beam chamber and α is steady-state offset of beam center.

From the analyses with parameters in table 2, it is found that the intrinsic stabilization of the coupled system of RF cavity and electron beams works well as far as the perturbation of the cavity voltage does not exceed 2%. Figure 4 shows the time profile of the cavity voltage and beam current when perturbation of 2% is applied to the cavity voltage at $t = 0.1$ms.

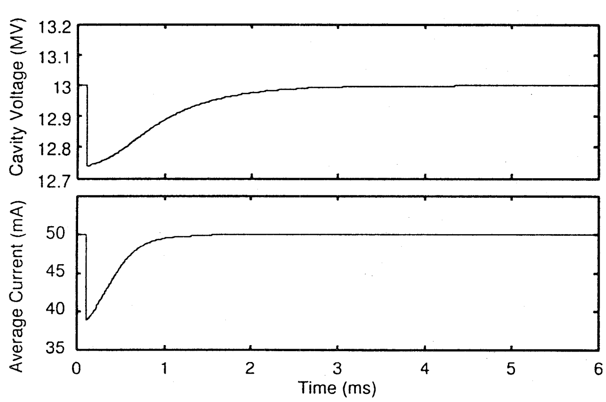

Fig. 4 Time profile of cavity voltage and average beam current. (2% perturbation is applied to the cavity voltage at $t = 0.1$ms.)

The analysis shows that the RF system is stable itself for perturbation less than 2%, but the settling time longer than 1ms is not practical. The response time of stabilization can be greatly improved by simple feedback loops for the RF amplitude and phase control, which is similar to a control-system used at JAERI-FEL and has a transfer function: $G/(1+sT)$. The analysis shows that perturbation larger than 10% can be quickly corrected with the feedback loops. Figure 5 shows an impulse of field perturbation is compensated by feedback loops.

4 Conclusions

Design of recirculation transport for the energy-recovery experiment planed at JAERI-FEL has been

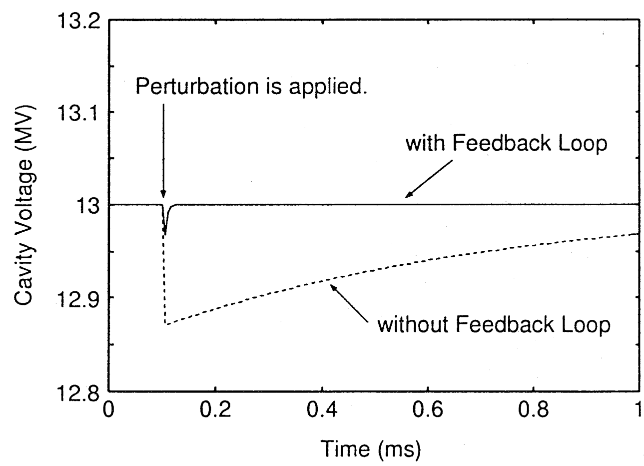

Fig. 5 RF field stabilization with a feedback loop.

presented. It has been found that an isochronous lattice of triple-bend arc meets the design requirements for the energy-recovery. The energy acceptance of the designed arc is large enough to avoid beam loss during the recirculation and the phase error at reinjection never occurs owing to second-order isochronicity of the arc. The nonlinear analysis of RF stability shows that the RF system is stable, if the perturbation is less than 2%. By adding a simple feedback loop to the RF amplitude and phase control, perturbation larger than 10% can be corrected within 20 μs.

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