TOLERANCE STUDY ON RF AMPLITUDE AND PHASE OF MAIN SUPERCONDUCTING CAVITIES AND INJECTION TIMING FOR THE COMPACT ERL

N. Nakamura, ISSP, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, 277-8581 Chiba, Japan
M. Shimada, T. Miyajima, Y. Kobayashi, S. Sakanaka.
High Energy Accelerator Research Organization(KEK), Tsukuba, 305-0801 Ibaraki, Japan
R. Hajima, Japan Atomic Energy Agency(JAEA), Tokai, 319-1195 Ibaraki, Japan

Abstract

Tolerance study on RF amplitude and phase of main superconducting(SC) cavities and injection timing was performed for the compact ERL. As a result, it was found that errors of the RF amplitude and phase should be controlled down to the level of 0.01 % and 0.01° in rms, respectively, in order to satisfy requirements for the arrival time and the bunch length in bunch compression mode. In high current and low emittance modes, these control errors can be relaxed to the level of 0.1 % and 0.1° for early operation, though the RF amplitude error should be reduced to the level of 0.01 % in future to improve the momentum variation. The injection timing error is allowed up to at least 200 fs in all the operation modes.

INTRODUCTION

In ERL-based light sources, higher accuracy is expected to be required for RF control and timing, because the beam has shorter bunch length and smaller momentum (energy) spread compared with that of the existing ring-based synchrotron radiation(SR) sources. We have studied effects of RF amplitude and phase variations of main superconducting(SC) cavities and effects of timing jitter of beam injection from an injector with simulation in order to know requirements for the RF control and the injection timing.

Figure 1 shows layout of the compact ERL[1] used for this study. The compact ERL has two TBA(Triple Bend Achromat) arc sections and eight main SC cavities in cryomodules. Basic parameters for three operation modes are listed in Table 1. It is assumed in this simulation study that the bunched beam has a six-dimensional Gaussian distribution just after the merger as the initial conditions and all errors of the injector except injection timing jitter are not considered. In this paper, we present simulation results for the three operation modes and discuss individual tolerances for RF amplitude and phase errors and injection timing error.

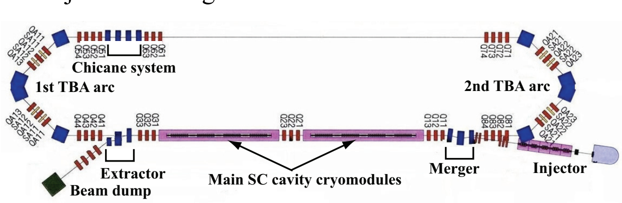

Figure 1: Layout of a 1-loop compact ERL.

Table 1: Basic Parameters of the Compact ERL for Three Operation Modes (HC: High Current Mode, LE: Low Emittance Mode, BC: Bunch Compression Mode)

Parameter	HC	LE	BC
RF frequency[GHz]	1.3		
Injection energy[MeV]	5		
Number of main SC cavities	8		
Effective cavity length[m]	1		
Accelerating field[MV/m]	15		
Repetition rate [GHz]	1.3	1.3	≤ 0.001
Average beam current[mA]	100	10	-
Bunch charge[pC]	77	7.7	≥ 77
Emittance[1)][mm·mrad]	1	0.1	-
Bunch length[ps]	2	2	< 0.1

[1)] Normalized emittance

BUNCH COMPRESSION MODE

Beam Parameters and Optics

In this mode, bunch charge of 77 pC, initial rms normalized emittance of 1 mm mrad, initial rms bunch length of 1 ps, and initial rms momentum spread of 2×10^{-3} are assumed. The beam is accelerated off-crest by the eight main SC cavities with the accelerating field of 15 MV/m and compressed by the 1st TBA arc section with non-zero R_{56}. Since the RF phase of the main SC cavities ϕ_{RF} is set at about 15 degrees, the beam energy after the acceleration is about 121 MeV. The R_{56} value of the 1st TBA arc section is set at 0.131 m and the fields of the sextupole magnets in the 1st TBA arc section are optimized to minimize the bunch length at the exit of the 1st TBA arc section[1]. When momentum of an electron is deviated from the reference momentum p by Δp, the arrival time of the electron is changed by

$$\Delta T \cong \frac{R_{56}}{v}\frac{\Delta p}{p} \tag{1}$$

Here v is the electron velocity.

Effects of RF Amplitude Error

Variations of the arrival time and the bunch length at the exit of the 1st TBA arc section due to RF amplitude error of the main SC cavities are obtained with a simulation code “elegant”[2]. Figure 2 shows the change of 2D electron distribution of the bunch on arrival time-momentum plane for the RF amplitude error of -0.5 % to

0.5 % in 0.1 % step. The bunch arrival time is clearly increased with the RF amplitude. Furthermore, as the RF amplitude error becomes large, the bunch is inclined toward the right or left side on the plane and as a result the bunch length is increased. Figure 3 shows the arrival time and bunch length variations due to the RF amplitude error. The arrival time variation is almost linear and 410 fs for the RF amplitude error of 0.1 %. This is consistent with the time variation calculated from $\Delta p/p \approx \Delta V/V$=0.001, R_{56}=0.131 m and Eq. (1). The bunch length variation is parabolic around the reference RF amplitude and much smaller than the arrival time variation. The bunch length is about 55 fs without the error. In order to keep the effective bunch length including the arrival time variation within 60 fs and 100 fs, the RF amplitude error should be less than 0.005 % and 0.02 % in rms, respectively.

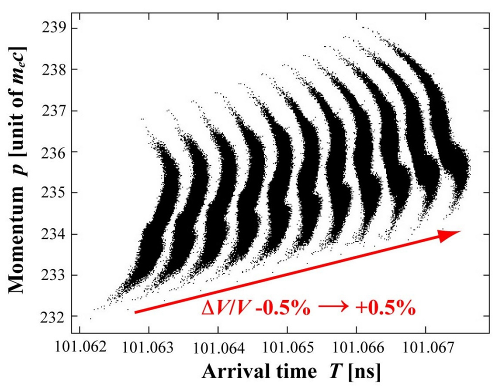

Figure 2: Change of 2D electron distribution of the bunch on the arrival time-momentum plane for the RF amplitude error of -0.5 % to 0.5 % in 0.1 % step.

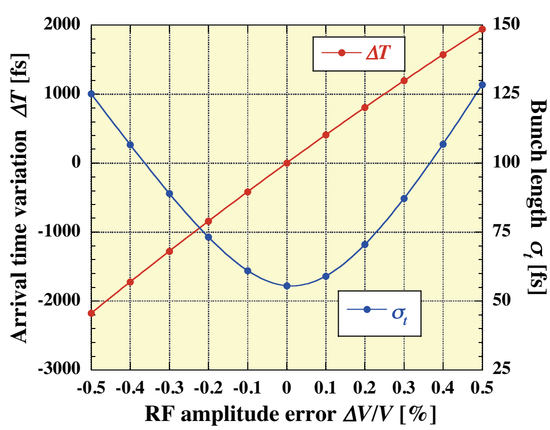

Figure 3: Variations of the arrival time and the bunch length due to the RF amplitude error.

Effects of RF Phase Error

Like the RF amplitude error, the RF phase error causes variations of the arrival time and the bunch length. The simulated change of 2D electron distribution of the bunch for the RF phase error of -0.5° to 0.5° in 0.1° step is shown in Fig. 4. The arrival time is increased with decreasing the RF phase. The bunch length is increased as the RF phase error becomes large. Figure 5 shows the arrival time and bunch length variations due to the RF phase error. The arrival time variation is almost linear and 200 fs for the RF amplitude error of 0.1°. This is also consistent with the time variation calculated from $\Delta p/p \approx \Delta\phi_{RF} \times \tan\phi_{RF}$=0.00047, R_{56}=0.131 m and Eq. (1). The bunch length variation is negligibly smaller than the arrival time variation. The RF phase error should be suppressed to 0.01° and 0.04° in rms to keep the effective bunch length within 60 fs and 100 fs.

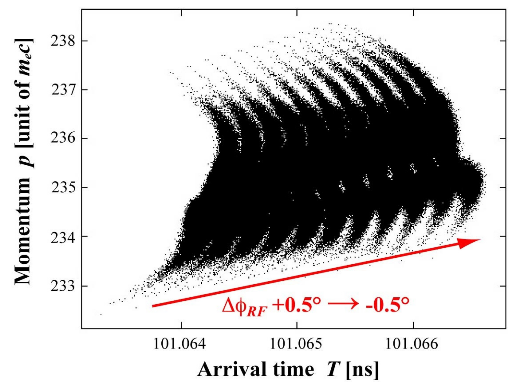

Figure 4: Change of 2D electron distribution of the bunch on the arrival time-momentum plane for the RF phase error of -0.5° to 0.5° in 0.1° step..

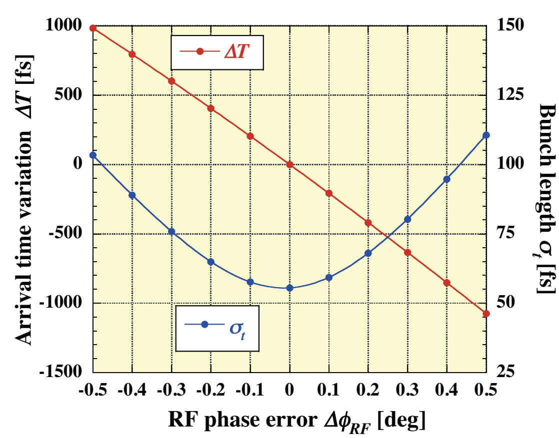

Figure 5: Variations of the arrival time and the bunch length due to the RF phase error.

Effects of Injection Timing Error

Effects of Injection timing error were obtained from the effects of the RF phase error. The arrival time variation due to the injection timing error is the sum of the injection timing error Δt_{inj} and the arrival time variation due to the RF phase error $\Delta\phi_{RF}=2\pi f \Delta t_{inj}$, where f is the accelerating frequency. On the other hand, the bunch length variation is equal to that due to the RF phase error. The arrival time and bunch length variations due to the injection timing error are shown in Fig. 6. The arrival time variation is only less than 10 fs for the injection error of 200 fs. This is because the injection timing error is almost cancelled by the arrival time variation due to the RF phase error caused by the injection timing error. The bunch length variation is less than 5 fs for the injection error of 200 fs. Possible injection timing error due to the gun ripple and RF amplitude and phase errors of injection cavities was already evaluated with simulation to be less than 200 fs, though it was usually coupled with the other beam parameters[3]. Here only the injection timing is changed.

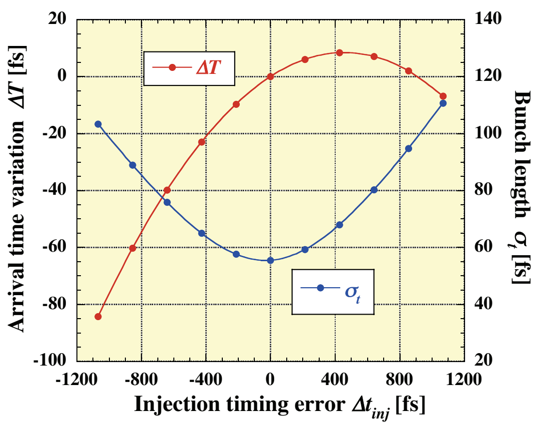

Figure 6: Variations of the arrival time and the bunch length due to the injection timing error.

HIGH CURRENT AND LOW EMITTANCE MODES

Bunch charge of 77 and 7.7 pC and initial normalized emittance of 1 and 0.1 mm mrad are assumed in HC(high current) and LE(low emittance) modes, respectively. In both modes, initial bunch length of 2 ps, and initial momentum spread of 2×10^{-3} are assumed. The beam is accelerated on-crest by the eight SC cavities with the accelerating field of 15 MV/m and the beam energy after the acceleration is about 125 MeV. The R_{56} value of the 1st TBA arc section is set at 0 m and the sextupole magnets in the 1st TBA arc section are turned off.

Table 2 summarizes the variations of momentum, momentum spread, horizontal and vertical normalized emittances as well as the arrival time and bunch length at the exit of the 1st TBA arc due to RF amplitude error in HC and LE modes, together with those in BC mode for comparison. The arrival time variations for all the errors in HC and LE modes are negligibly small for the bunch length of 2 ps. Variations of the other beam parameters in HC and LE modes are also not serious for the compact ERL. However the RF amplitude error should be finally reduced by one order of magnitude, because the momentum variation due to the RF amplitude error of ±1 % is much larger than the momentum spread without the error (1.7×10^{-4} for HC mode and 2.0×10^{-4} for LE mode) at the exit of the 1st arc section. In BC mode, all the momentum variations in Table 2c are smaller than the momentum spread of 2.6×10^{-3} at the 1st arc exit.

Table 2: Variations of Parameters due to RF Amplitude and Phase Errors and Injection Timing Error.

(a) HC mode

Error	$\Delta V/V$ -0.1/0.1 %	$\Delta\phi_{RF}$ -0.1/0.1 °	Δt_{inj} -200/200 fs
Arrival time	-25/1.3 fs	-0.11/0.16 fs	-200/200 fs
Bunch length	< 1 %	< 1 %	< 1 %
Momentum	-0.1/0.1 %	< 0.0002 %	< 0.0002 %
Momentum spread	< 1 %	-4.7/7.1 %	-4.4/6.6 %
Hor. emittance	< 1 %	< 1 %	< 1 %
Vert. emittance	< 1 %	< 1 %	< 1 %

(b) LE mode

Error	$\Delta V/V$ -0.1/0.1 %	$\Delta\phi_{RF}$ -0.1/0.1 °	Δt_{inj} -200/200 fs
Arrival time	-24/2.4 fs	-0.02/0.08 fs	-200/200 fs
Bunch length	< 1 %	< 1 %	< 1 %
Momentum	-0.1/0.1 %	< 0.0002 %	< 0.0002 %
Momentum spread	< 1 %	< 2 %	< 2 %
Hor. emittance	< 1 %	< 1 %	< 1 %
Vert. emittance	< 1 %	< 1 %	< 1 %

(c) BC mode

Error	$\Delta V/V$ -0.1/0.1 %	$\Delta\phi_{RF}$ -0.1/0.1 °	Δt_{inj} -200/200 fs
Arrival time	-417/408 fs	204/-208 fs	-9.7/6.0 fs
Bunch length	9.9/6.3 %	3.8/6.7 %	3.6/6.3 %
Momentum	-0.09/0.09 %	-0.05/0.04 %	-0.04/0.04 %
Momentum spread	< 1 %	< 2 %	< 2 %
Hor. emittance	-2.3/5.5 %	2.7/-1.1 %	2.5/-1.0 %
Vert. emittance	4.5/-1.6 %	-1.3/2.1 %	-1.2/2.0 %

SUMMARY

From the tolerance study, in bunch compression mode, required stability of the RF amplitude and phase of the main SC cavities should be the level of 0.01% and 0.01° to avoid significant increase of the effective bunch length including the arrival time variation. In high current and low emittance modes, stability of 0.1 % and 0.1° is enough for early operation of the compact ERL, though stability of the RF amplitude should be improved to the level of 0.01 % for making the most of the small momentum spread in future. The injection timing error of 200 fs is enough for preserving the beam quality in all the operation modes. Similar error analysis can be applied to the 2-loop compact ERL[4].

ACKNOWLDGEMENTS

We would like to thank Dr. M. Borland(APS) for his help with our simulations.

REFERENCES

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