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著者(和文)	菊池崇志
Author(English)	Takashi Kikuchi
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Outline:
Theoretical Analysis of Emittance Growth for Intense Charged Particle Beam with Thermal Equilibrium Distribution During Longitudinal Pulse Compression

Takashi Kikuchi（菊池　崇志）

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Introduction

Heavy-Ion Inertial Fusion and Particle Accelerator System

An inertial confinement fusion (ICF) system is expected to be one of the next electrical power generations [1–3]. Heavy-ion inertial fusion (HIF), an ICF method driven by irradiation of intense heavy-ion beams, requires a particle beam driver, which is capable of high-current heavy-ion acceleration [4]. Not only the HIF system, but also ion-beam-driven warm dense matter (WDM) and high energy density physics (HEDP) [5, 6] require the generation of a high-current heavy-ion beams (HIBs) [7–10]. The beam pulse duration is adjusted by the implosion time scale of the fuel pellet in the HIF system [11]. For this reason, longitudinal pulse compression is required for the heavy-ion beam in the final stage of the HIF accelerator system. The intense HIB evolves in the space-charge-dominated state, and the beam parameters are far from those of the conventional particle accelerators [12]. Table 1 shows the various implosion schemes [13–16] and the typical beam parameters for the HIF systems [17]. Therefore, the beam dynamics and its control in the space-charge-dominated regime are important topics of research in these fields [18].

At the final stage of the particle accelerator system in the HIF driver, the ion beam pulse should be longitudinally compressed into the range of 10–100 ns [19, 20]. Typical beam parameters in the final stage of the HIF accelerator complex are as shown in Table 2 [21, 22]. For effective target experiments, we must compress and transport the ion bunch with an emittance growth lower than an allowable level. In case of intense ion beam propagation, a dilution of particle distribution in the phase space can cause emittance growth because of the collective relaxation from a non-equilibrium particle distribution to a more thermalized state [23]. For this reason, the final pulse compression and final focusing are the key technologies in the driver systems.

A neutralized pulse compression scheme was proposed, experimentally

Table 1: Implosion schemes and typical beam parameters for HIF [17]. The number inside the brackets ( ) indicates the beam number for the fast ignition.

Scheme	Total Beam Energy	Kinetic Energy	Total Beam Current	Beam Number	Peak Beam Power
Direct Drive	$\sim$Several MJ	$\sim$10 GeV	$\sim$10 kA	$\geq$32	$\geq$Several 100 TW
Indirect Drive	$\sim$3 MJ	2$\sim$4 GeV	$\sim$10$\sim$80 kA	$\sim$48	$\sim$470 TW
Cylindrical Target	7.5 MJ	100 GeV	$\sim$1 kA (20 kA)	1 (1)	$\sim$100 TW (2 PW)
X Target	5 MJ	90 GeV	$\sim$12 kA ($\sim$160 kA)	2 (1)	1000 TW (15 PW)

Table 2: Typical example of beam parameters for final stage of HIF accelerator complex.

Ion species	Pb^{1+}
Number of ions	6.25×10^{14}
Kinetic energy [GeV]	10
Initial beam current [A]	400
Final beam current [kA]	10
Initial pulse duration [ns]	250
Final pulse duration [ns]	10

demonstrated [24, 25], and theoretically and/or numerically investigated [26–29]. However, pulse compression scenarios without charge and current neutralization mechanisms were proposed and studied using theoretical and numerical approaches over several years [30–36].

In the fields of WDM, HEDP [5, 6], and inertial confinement fusion based on ion beam heating, a large ion beam power should be focused in the local volume of a target to reach a higher energy density state [7]. The input power is proportional to the product of the kinetic energy and the beam current. Since high-current ion beams are necessary for these applications, the physics and dynamics of space-charge-dominated beams are crucial issues in WDM, HEDP, and HIF researches.

Beam Physics

Transport of space-charge-dominated beams with a low-emittance condition is particularly important in applications such as WDM science [5, 6] and HIF [7–9, 37–40]. To generate a localized high energy density state, a particle beam with a high current and a rather low kinetic energy must be focused onto a small spot on a target. The beam emittance is one of useful indices for the description of the beam quality and volume in phase space. As the beam with a large volume in phase space cannot be focused onto a small area, the production of an intense and low-emittance beam is of great significance for those applications [41, 42]. In high-power accelerators, beam merging, bunching, and compressing are essential to generate an intense beam. The particle distribution often reaches a non-equilibrium state during beam manipulations, and it sometimes has a large free energy.

A nonuniform charge distribution of a beam can cause a significant emittance growth, especially in the space-charge-dominated regime [23, 43, 44]. Wangler et al. derived a differential equation for the emittance evolution along the beam transport [43]. Reiser summarized the relation between free energy and the accompanied emittance growth in nonstationary beams [44]. Lund et al. showed the thermal relaxation of initially extreme nonuniform distribution and emittance growth using theoretical estimation and numerical simulations [23].

Intense charged particle beam transport with lower emittance is a key issue in pulsed high-current beam applications such as ICF, high energy density science, and WDM researches, driven by HIBs [37]. The emittance is an index of beam quality, and is defined as a statistical value in phase space [45–47]. From the viewpoint of the second law of thermodynamics, the emittance does not essentially decrease without a special operation such as beam cooling [48]. Consequently, charged particle beams should be transported without excessive emittance growth because large-emittance beams degrade the ability to focus onto a small spot on a target.

In general, a radially matched beam follows to an equilibrium condition, which depends on the radial (transverse) confinement force and the repulsion force composed of gradients of the space charge potential and the thermal pressure [45–47, 49, 50]. Figure 1 shows the balance between the confinement and the repulsion forces. The rms emittance of a general particle distribution $f(x, x')$ in the transverse (x) direction is defined by [47]

$$\varepsilon_{\text{rms}}^2 = \langle x_p^2 \rangle \langle x_p'^2 \rangle - \langle x_p \, x_p' \rangle^2 = \langle x_p^2 \rangle \frac{\langle v_p^2 \rangle}{v_0^2} - \frac{\langle x_p \, v_p \rangle^2}{v_0^2} \ , \tag{1}$$

where x_p is the position of p-th particle in real space, the prime ($'$) denotes

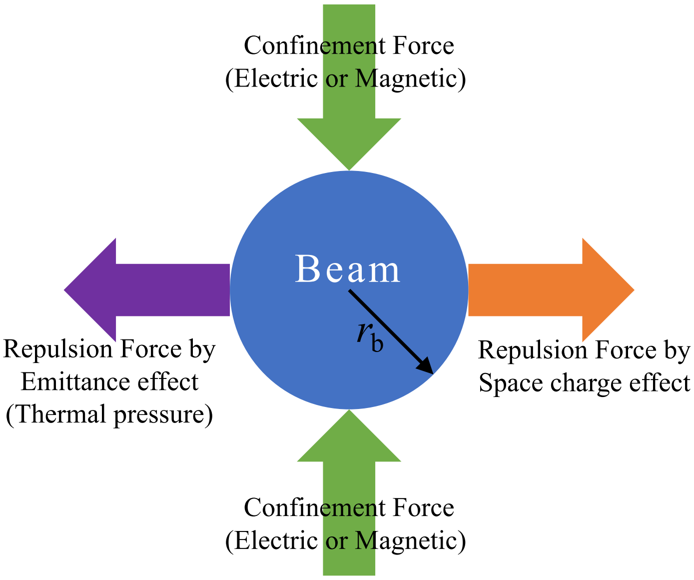

Figure 1: Confinement and repulsion forces and its balance in beam.

the derivative in the longitudinal direction, $v_p = dx_p/dt$ is the velocity of p-th particle in x-direction, and v_0 is the beam (average, center–of–mass) velocity. The value $\langle X \rangle$ indicates the average of X. When the space charge potential energy is converted into thermal (kinetic) energy, the rms emittance will increase with the increase of $\langle v_p^2 \rangle$ and $\langle x_p\, v_p \rangle$ as shown in Eq.(1).

In an azimuthally symmetric beam, the nonlinear evolution of the unnormalized emittance ε in transport distance s is described by [45]

$$\frac{d\,\varepsilon^2}{ds} = r_{\mathrm{b}}^2 \left(-\frac{K}{2\, r_{\mathrm{b}}} \frac{d\, r_{\mathrm{b}}}{ds} - \frac{dE_{\mathrm{sf}}}{ds} \right), \tag{2}$$

where r_{b} is the beam radius, K is the self-field perveance, and E_{sf} is the normalized self-field energy. Eq. (2) indicates that the emittance change is driven by the beam radius and/or the self-field energy changes. Reiser developed the expression for the possible emittance growth due to the nonuniform charge distribution, mismatched beam, and off-centered beam to introduce a free-energy parameter [44]. The analysis was permored with the assumption that the beam radius remains constant in the case of the nonuniform charge distribution. However, it is expected that the beam radius increases actively in the case of the longitudinal bunch compression, because of the space charge effect [34, 35, 51, 52].

The emittance growth is induced by several factors. The “possible” emittance growth induced in the nonuniform charge distribution, mismatched beam, and off-centered beam was developed with the free–energy parameter [44]. In the case of the nonuniform charge distribution, the possible emittance growth $\varepsilon_f/\varepsilon_i$ (ε_f is the emittance in the final state, and ε_i is the emittance in the initial state) is written as a function of the nonlinear field energy factor U/w_0, which is a dimensionless parameter, and tune depression σ/σ_0, which is an index of space charge strength (σ and σ_0 are the depressed and undepressed phase advances per lattice period) [44, 53–55],

$$\frac{\varepsilon_f}{\varepsilon_i} = \left[1 + \frac{1}{2}\left(\frac{1}{\sigma^2/\sigma_0^2} - 1\right)\frac{U}{w_0}\right]^{1/2}. \tag{3}$$

The nonlinear field energy factor U/w_0, which depends on the radial density distribution, is given as a function of the field energy per unit length within the actual beam volume and the field energy difference per unit length between nonuniform and uniform beams [44, 53–57]. The field energy difference per unit length between nonuniform and uniform beams is defined by

$$U = w - w_u. \tag{4}$$

Here, the field energy per unit length for an arbitrary particle distribution is obtained from

$$w = \pi\,\epsilon_0 \int_0^{r_p} {E_r}^2\, r\, dr, \tag{5}$$

where r_p is the inner radius of vacuum pipe, ϵ_0 is the permittivity of free space, and E_r is the self-field in the radial direction r. The field energy per unit length for the uniform particle distribution is rewritten as [57]

$$w_u = w_0\left(1 + 4\ln\frac{r_p}{r_b}\right), \tag{6}$$

where r_b is the (rms edge) beam radius. Here the field energy per unit length within the actual beam volume is written as

$$w_0 = \frac{\lambda^2}{16\,\pi\,\epsilon_0}, \tag{7}$$

where λ is the line-charge density of beam. Equation (3) implies that the space–charge–effect–induced change in emittance is driven in the condition of $U/w_0 \neq 0$. The condition of $U/w_0 = 0$ is applied in the uniform charge density in real space associated with the Kapchinskij-Vladimirskij (KV) distribution in phase space. The linear-Courant-Snyder invariant distributions with a nonuniform charge density in real space, such as the waterbag (WB), Gaussian (GA), parabolic (PA), and semi-Gaussian (SG) profiles, are not stationary and will change towards a more uniform charge distribution in real space. One of the possible and reasonable particle distributions is the thermal equilibrium or the Maxwell-Boltzmann distribution in a beam described by [47, 58, 59]

$$n(r) = \hat{n} \exp\left[-\frac{\gamma_b m \beta_b^2 c^2 k_{\beta 0}^2}{2k_B T} r^2 - \frac{1}{\gamma_b^2} \frac{q\phi(r)}{k_B T} \right], \tag{8}$$

where $\hat{n}$ is the number density at the axis, γ_b is the relativistic factor, m is the mass of the beam particle, β_b is the beam velocity divided by the light speed c, $k_{\beta 0}$ is the wavenumber of the betatron oscillation without the space charge effect, $k_B T$ is the beam temperature, and $\phi(r)$ is the space charge potential. The thermal equilibrium profile also will change towards a more uniform distribution in real space. Consequently, a nonuniform charge distribution such as a non-KV distribution has a source of rms emittance growth ($U/w_0 \neq 0$). A possible emittance growth induced by the space charge potential via free energy was introduced [44, 53–55, 57], which indicates the highest range of emittance growth due to the space charge effect, i.e., the maximum emittance growth for nonstationary distribution.

The equilibrium radial density profile is redistributed according to the balance between the space charge and thermal potentials. However, the beam current increase owing to longitudinal bunch compression causes dynamically the unbalanced state. During the longitudinal bunch compression, the parameters of charged particle beams are changed, and the beam current is also increased owing to the increase of the charge density. Not only thermal equilibrium distribution but also the linear-Courant-Snyder invariant distributions, such as the KV, WB, GA, PA, and SG distributions, change with the increase of beam current, which redistributes the radial density profile during the longitudinal pulse compression [60]. A finite nonlinear field energy factor induces an emittance growth because the space charge potential can be thermalized. The possible emittance growth was estimated with the thermal equilibrium distribution [57, 61], and it was shown that it has the maximum value in a low tune depression regime [62], as a static analysis.

For this reason, one of the factors for the emittance growth resulted in the redistribution of density profile, caused by the longitudinal pulse compression. Wangler *et al.* showed the differential equation of the emittance growth with the change in the nonlinear field energy factor [43, 46, 47]. As a result, if the change of the nonlinear field energy factor is clear, the emittance growth can be evaluated.

In this situation, the charged particle beams evolve from an emittance-dominated state to a space-charge-dominated state during a short time period. During the longitudinal pulse compression, the beam parameters change dynamically. It is difficult to estimate theoretically the particle motions in the beam bunch because the behaviors of many particles involve a dynamically changing collective effect.

A charged particle beam is an assembly of many particles with the same polarity charge. Charged particle beams are transported to a target with external applied electrostatic and/or magnetic fields to confine the beam bunch in the radial direction. The radial confinement force balances with the repulsion forces through thermal motion and Coulomb interaction. The particle distribution inside the beam and the beam radius are determined by the balance, and the particle beam is in an equilibrium state. When the equilibrium particle distribution exhibits a nonlinear field, the electromagnetic energy of the beam is converted into thermal energy driven by the space-charge field. As a result, the equilibrium particle distribution will be transformed into the another equilibrium particle distribution.

Scope of This Thesis

As introduced in the previous section, the beam physics in a space-charge-dominated regime has been studied for several years. However, ideal beam conditions, such as the KV, WB, GA distributions, were assumed. In addition, the beam parameter was analyzed as constant.

In this thesis, the emittance growth of charged particle beams in the space-charge-dominated state is theoretically estimated. The beam physics is theoretically modeled in the region ranging from a single particle orbit behavior to multi–particle motions. Consequently, the theoretical analysis of the emittance growth with more realistic conditions is proposed in this thesis.

The possible emittance growth for the thermal equilibrium particle distribution is modeled theoretically. The statistical emittance increases with the balance between the thermal and electromagnetic energies of the beam because the thermal equilibrium state changes into another thermal equilibrium state during the beam parameter change. The emittance growth is driven by the nonlinear electromagnetic field induced by the nonuniform charged particle distribution.

The static analysis of the possible emittance growth is described for the thermal equilibrium distribution. The possible emittance growth is indicated by the tune depression and the nonlinear field energy factor. The calculation procedure is also described without a constant radius approximation. The dynamic analysis of the possible emittance growth is carried out using the

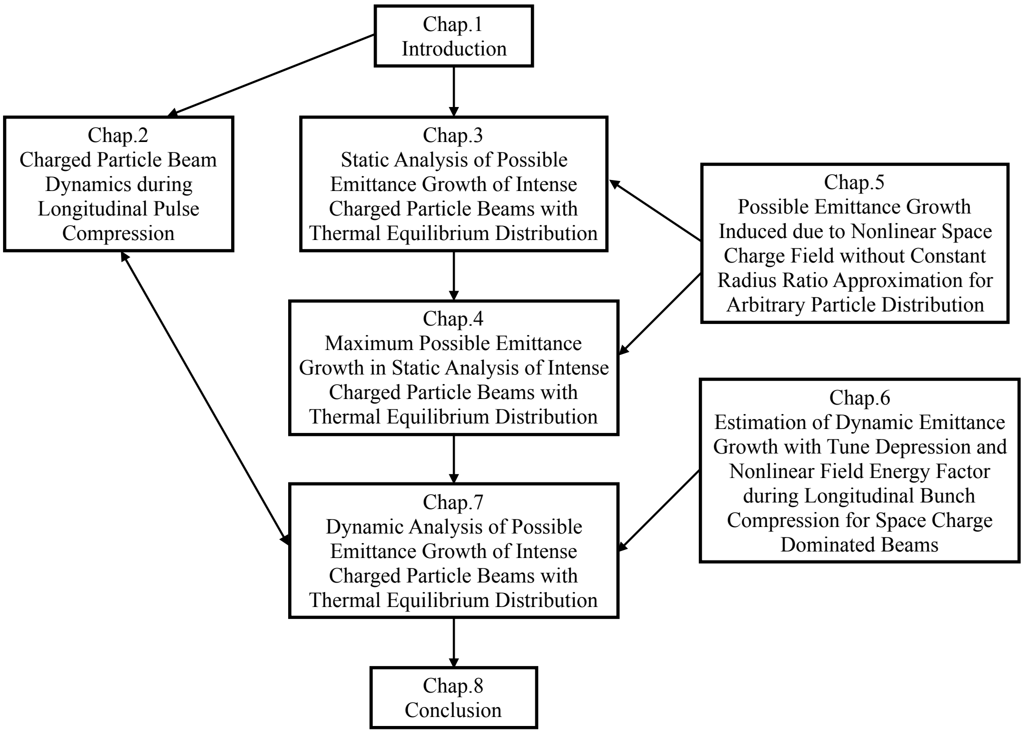

Figure 2: Organization and liaison between chapters in this thesis.

nonlinear field energy factor at each initial particle distribution, and the estimations are compared to the numerical simulation results. The dynamic estimation of the possible emittance growth is modeled using the thermal equilibrium distribution. In comparison with the numerical simulation and the experimental results, the author shows that the proposed theoretical model is suitable for the estimation of the emittance growth during the longitudinal pulse compression.

Figure 2 shows the organization and the liaison between the chapters in this thesis.

In Chapter 2, the beam dynamics is studied numerically using multi–particle tracking, and the outline of the beam behavior and the emittance growth for the longitudinal pulse compression are introduced [63, 64].

In Chapter 3, the analytical model for the possible emittance growth is established for the thermal equilibrium distribution [57]. The equilibrium particle distribution is determined by the balance between the thermal energy and the electromagnetic energy in the beam. The electromagnetic energy in the beam bunch is converted into thermal energy via the space-charge field in the nonuniform profile.

In Chapter 4, the approximated solution for the possible emittance growth for the thermal equilibrium is derived as a function of the tune depression using a fitting function [62]. The maximum possible emittance growth is indicated using the tune depression in the space-charge-dominated regime using an approximated solution.

In the conventional model for the possible emittance growth estimation, the beam radius is assumed as constant. On the other hand, the beam radius increases with the increase of the beam current driven by the longitudinal pulse compression in the final stage of the HIF accelerator system. In Chapter 5, the possible emittance growth without the constant radius condition is modeled [61].

The static analysis for the beam parameter is investigated in the previous chapters. However, the space charge effect changes with the longitudinal pulse compression in the final stage of the HIF accelerator system. Therefore, the dynamic emittance growth is studied with the change of the space charge effect in Chapter 6 [65]. In addition, the estimated dynamic emittance growth is compared with the numerical result shown in Chapter 2.

In Chapter 7, the dynamic analysis for the possible emittance growth is estimated during the longitudinal pulse compression using the dynamic model introduced in the previous chapter for the thermal equilibrium model investigated in Chapters 3 and 4. In addition, the dynamic estimation for the possible emittance growth for the thermal equilibrium distribution is investigated and compared with the numerical simulation result described in Chapter 2 and the previous experimental result [66, 67].

In Chapter 8, the results of the analysis on the dynamic emittance growth for the charged particle beams with the space-charge-dominated state are reviewed, and this thesis is summarized.

Conclusion

In this chapter, the conclusion of this study is summarized as follows.

In Chapter 2, the beam dynamics with varying beam parameter was numerically explained using multi-particle tracking.

The pulse compression of the intense HIB with the space-charge-dominated state is the key technology in the driver systems for the researches of HIF, WDM, and HEDP. A high-current HIB dynamics during beam transport with a longitudinal pulse compression was numerically investigated using a 3D particle simulation code. The code in use was developed to solve the 3D particle motions including the gamma-factor corrections as the effect of a self-magnetic field with the reduced electric field due to the space-charge effect and the external magnetic field for the transverse confinement of the beam.

The results were compared with the 2D simulation including the longitudinal current increase model. The current increase model in the 2D calculation could simulate the density increase in the 3D calculation with an initial linear velocity tilt. In addition, the transverse emittance growth was increased along the beam transport due to the longitudinal motion of the beam particle.

The 3D beam behavior was also compared to the longitudinal 1D calculation with a constant geometry factor as a model of the transverse direction. It was considered that the longitudinal beam dynamics would not be dominated by the transverse motions of the beam.

The beam parameters were intrinsically not stationary because the beam current increased along the beam transport line due to the velocity tilt applied. However, the beam condition seemed to be under equilibrium in the beam parameter region discussed in this thesis.

According to the above discussions, the transverse 2D view in the cross section of the beam represents the beam dynamics fairly well during the longitudinal pulse compression.

The halo particle generation and the emittance growth were studied during the bunch compression with the high beam current. The orbits of the generated halo particles were extended along the beam transport with the beam current increase. The generated halo particles could contribute to the emittance growth, and the orbit extension of the halo particles is a source of the beam loss.

The halo particle generations depended on the initial beam distribution. A Gaussian distribution has a long tail in the distribution; however, a parabolic distribution has no particles near the edge of the beam. At the edge of the Gaussian distribution, a beam particle has various betatron oscillation frequencies along the beam transport. Resonance overlapping must lead to halo generation.

When the particle distribution can be controlled in the near initial state, halo particle generation can be suppressed in the drift compression of high-current beams.

As discussed in the following chapters, the possible emittance growth induced by the redistribution of the charged particles was considered in this study. For this reason, the above discussion with the halo particle generation and its emittance growth is not the main scope of this thesis.

In Chapter 3, the particle distribution $n(r)$ along the radius and the nonlinear field energy factor U/w_0 depend on the tune depression for the thermal equilibrium distribution. Although U/w_0 of the thermal equilibrium beam increases when the tune depression is approximately unity, the σ/σ_0 term compensates the increase of the possible emittance growth. It can be shown by the static analysis that by keeping the beam under the thermal equilibrium condition, the possible emittance growth can be suppressed effectively.

It is considered that the thermal equilibrium distribution produces a general particle profile. Consequently, the static analysis discussed in this chapter gives the possible emittance growth in general beam cases.

In Chapter 4, the maximum possible emittance growth in the charged particle beams with the thermal equilibrium distribution during the transport in the focusing channel was theoretically indicated as a function of the tune depression. The nonlinear field energy factor was expressed using a simple fitting function from the results of the analysis of the possible emittance growth. Unlike in the case of the Gaussian distribution, the possible emittance growth with the thermal equilibrium distribution has a maximum point, which is a small value. For example, in the energy driver of HIF, the tune depression may be approximately $\sigma/\sigma_0 = 0.1494$; however, the highest emittance growth is expected to be 1.0348.

In Chapter 5, the calculation procedure was developed to obtain the ratio of the beam radii at the final and initial states in arbitrary particle distributions, and it was applied to the estimation of the possible emittance growth for the Gaussian and thermal equilibrium distributions. The final and initial beam radius ratio was not exactly constant ($a_\mathrm{f}/a_\mathrm{i} \neq 1$). However, the discrepancy was predicted as a few percent at the highest. The ratio was expected to be under 0.7 % in the whole range of the tune depression for the thermal equilibrium distribution.

The possible emittance growth as a function of the tune depression and nonlinear field energy factor, with and without the constant radius ratio approximation, was also estimated for both the Gaussian and thermal equilibrium distributions. The discrepancies between the cases with and without the constant radius ratio were small, and it was confirmed that the emittance growth is similar in all distributions, even in the case without constant radius ratio approximation.

Consequently, the estimation of the possible emittance growth with the assumption that the beam radius remains constant, which was developed by Reiser [44], is appropriate enough and is a useful formula in the entire range of the tune depression for arbitrary particle distribution.

In Chapter 6, the dynamic emittance growth during the beam transport was estimated theoretically as a function of the tune depression and nonlinear field energy factor with various initial particle distributions. The tune depression was given by the initial beam parameters and the beam current including the bunch compression. The nonlinear field energy factor was obtained using numerical simulation examples. By comparing the analytical and numerical simulation results, the analytically estimated emittances were larger than the numerical result.

In the initial distribution with the space-charge-induced instability, the integrated possible emittance growth was not applicable. However, the overestimation was 14 % in the worst case, and the beam for the distribution with the space-charge-induced instability is a special case such as KV distribution.

Consequently, it is expected that the dynamic estimation of the possible emittance growth as a function of the tune depression and nonlinear field energy factor with the bunch compression model is useful in estimating the emittance growth.

In Chapter 7, the dynamic emittance growth during the beam transport with the thermal equilibrium distribution was estimated theoretically. The approximated solution for the theoretical estimation was obtained and compared to the numerical and the experimental results. Consequently, the comparative results indicated that the relative error of the theoretical estimation is a few percent and less than 10 % at the highest.

Intrinsically, the integrated possible emittance growth obtained in this study gives the "possibility (the highest range)" of the emittance growth. When all of the free energy is converted to thermal energy, the integrated possible emittance growth corresponds to the numerical and the experimental results. For this reason, almost all of the estimation given for the possible emittance growth overestimates the emittance changes. (Only the possible emittance growth induced through the redistribution of the charged particles was included in this thesis. For this reason, the additional emittance increases, which are caused by the nonlinear external field, mismatched transport, off-centered beam condition, halo particle generation, and so on, will be accumulated in the possible emittance growth treated in this thesis in real life.) However, the comparison result of this study implied an agreement within ∼10 %. This indicates that the emittance change follows the beam current increase owing to the longitudinal pulse compression maintaining a "quasi–equilibrium" condition.

In summary, the author proposed a quasi–analytical method in this study, to predict the emittance evolution during the longitudinal bunch compression of high-current beams. At every position of the transport line, the equilibrium state can be defined using the beam parameters and the condition of the beam transport line. However, the equilibrium state changes depending on the progress of the bunch compression owing to the dynamically evolving beam parameters. Namely, the beam particles tend to progress dynamically from one equilibrium state to another by redistributing the charged particles. The progress depends on the nonlinear external field, off–centered beam condition, space-charge field, and interactions between them. The numerical simulations were the only method to understand the phenomena, because the situation is extremely complex.

The quasi–analytical method proposed in this thesis is based on the free energy factor of a nonuniform particle distribution and it can avoid the complex treatment of the many-body problem. In this method, it was assumed that all of the free energy changes to thermal energy at every position of the transport line. Then, the method can predict the highest range of the emittance growth under dynamically changing beam conditions. Although the method often overestimates the emittance growth depending on the relaxation level, it predicts the qualitative behavior fairly well.

The physics involved in this study deals with the transition process from one equilibrium state to another. The opinion and the result obtained in this study apply not only to the beam physics but also to more general physical problems in the "quasi–equilibrium" phenomena. ("Quasi–static" is a technical term in thermodynamics, where the condition is treated as the state being limited to a thermal equilibrium. However, the phenomenon treated in this study, i.e., the "quasi–equilibrium," is not limited to a thermal equilibrium. This is because not only the thermal equilibrium condition but also the beam equilibrium conditions allow the KV, WB, GA, PA distributions.) In order to understand the underlying mechanism of the complex situation, such as the behavior of many particles during the longitudinal pulse compression, an analytical method is required in addition to numerical simulations and experiments. The analytical method discussed in this thesis can predict the evolution of emittance in many particle interaction, without the detailed information about the particles. Finally, I would like to point out that the physics discussed in this study, including the concepts of free energy, its dissipation, and relaxation of non–equilibrium state, is common knowledge in understanding the various phenomena in our world.

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