論文の要旨

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論文題目　Theoretical studies on Doppler laser cooling of an ion beam in a storage ring and an emittance growth mechanism of intense hadron beams
(蓄積リングにおけるドップラーレーザー冷却および高強度ハドロンビームのエミッタンス増大機構に関する理論的研究)

The first artificial acceleration of charged particles to a high kinetic energy was performed nearly a century ago. Since then, a variety of machines that enable one to accelerate electrons, protons, heavy ions, and even anti-particles, have been invented for diverse experimental purposes. We now have linear accelerators of various kinds such as DTL (Drift Tube Linac), DAW (Disk-And-Washer structure), RFQ (Radio-Frequency Quadrupole linac), etc., and circular accelerators such as cyclotrons, synchrotrons, storage-ring colliders, etc. In the early 20th century, particle accelerators were mostly employed for fundamental physics purposes. The usefulness of charged-particle beams for other fields were, however, realized soon and, as a result, many accelerators began to be constructed all over world. For instance, both hadron and lepton machines have widely been used for radiation therapy. The so-called *photon factories* are also available in many countries now. To explore high-energy frontier, extremely large colliders have been built in Europe, the United States, and Asia.

The physical property of a charged-particle beam is characterized by “energy”, “intensity”, and “emittance”. Among them, the emittance is particularly important in almost all kinds of applications. This concept is defined as the volume occupied by the beam in six-dimensional phase space. To put it briefly, the emittance corresponds to the beam temperature. A beam of lower emittance is certainly more preferable because we can focus it thinner or generate a nearly parallel beam. The emittance is, however, an approximate invariant in regular accelerators that can be regarded as a sort of conservative dynamical system. Main components of an accelerator, i.e. multipole magnets, radio-frequency cavities, etc. yield conservative forces, which means that the phase-space volume of a beam is unchanged due to the Liouville’s theorem. We thus need to introduce some dissipative interaction in the machine to control the emittance artificially.

The process of improving the beam quality or, in other words, reducing the emittance is called “cooling” because the temperature becomes lower as the beam is compressed in phase space. There are only few cooling methods technically well-established and applicable to hadron beams; namely, electron cooling, stochastic cooling, and laser cooling. Electron cooling and stochastic cooling are very popular in the community. On the other hand, Doppler laser cooling has been employed only at three laboratories so far, despite the fact that this relatively new cooling technique can produce an ultracold ion

beam in principle. The TSR group of Max Planck Institute in Germany carried out the first proof-of-principle experiment, immediately followed by another attempt at the ASTRID ring in Denmark. These two teams succeeded in cooling the longitudinal beam motion, but unfortunately, it turned out that efficient cooling of the transverse betatron motion is very difficult to achieve in practice.

More than 10 years after the European attempts, a Japanese group constructed a compact cooler storage ring equipped with a Doppler cooling system. The ring is named "S-LSR" (Small Laser-equipped Storage Ring). The lattice design of S-LSR has been designed carefully to minimize possible beam heating due to collective resonance. Most importantly, the so-called "resonant coupling method" can be applied in this ring for indirect transverse laser cooling. The ultimate goal of this experiment is to crystallize an ion beam by reducing the beam temperature near the absolute zero. The cooling system, however, has some technical limitations. Careful optimization of the lattice and laser parameters is thus crucial for the best cooling performance. For this purpose, I carried out a number of systematic multi-particle simulations using the molecular dynamics (MD) code "CRYSTAL" developed at Hiroshima University. As demonstrated below, a one-dimensional quasi-crystalline state could be reached in S-LSR only by adjusting several parameters to optimum values.

There exist various sources of instabilities that seriously deteriorate the beam quality. As is well-known, the periodic nature of alternating gradient beam focusing gives rise to resonance under specific conditions. Even if the machine operating point is chosen sufficiently away from resonance lines, we may still need to care about wake fields, residual gases, electron clouds, colliding beams, etc. In a high-intensity hadron accelerator, serious beam heating can occur spontaneously even without all these external origins of instability. The strong Coulomb potential of an intense beam can be a source of root-mean-squared (rms) emittance growth when the beam is deviated from the perfect stationary state. Since it is practically impossible to provide an ideal matched beam at injection, such self-field-induced instability is an important issue that has to be studied in detail. The latter part of the present thesis is devoted to this issue.

In this thesis, I start from a brief overview of the standard beam orbit theory in Chapter 1 for later convenience. I then go to systematic MD simulations of laser cooling in Chapter 2 and search for the best set of fundamental parameters assuming the experimental condition of S-LSR. It is shown that a unique ultracold state of beam could be established by means of the resonant coupling method with optimum laser-cooling parameters. As mentioned above, Chapter 3 is devoted to the derivation of simple analytic formulas that allow us to make a quick estimate of rms emittance growth in an initially mismatched beam. The two-dimensional *free-energy model* developed by Martin Reiser is generalized to treat an ellipsoidal bunches of arbitrary aspect ratio. Theoretical predictions are compared with Particle-In-Cell (PIC) simulations.