

論文の要旨

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論文題目 Experimental Study of Low-Order Resonant Beam Instabilities
in Circular Accelerators Using a Linear Paul Trap
(線形ポールトラップを用いた円形加速器における低次共鳴不安定性に関する実験的研究)

Nowadays, a variety of charged-particle beams have been applied to diverse purposes including fundamental physics, radiation therapy, life sciences, industry, etc. Such a global trend in beam applications has made it more important to deepen our current understanding of the nonlinear collective behavior of beams. For instance, some of next-generation machines under consideration or in the design stage around the world are supposed to accelerate very intense hadron beams where individual particles strongly couple through their Coulomb self-fields. The particle motions are no longer independent but essentially correlated with each other. Needless to say, this kind of collective effect is extremely complex. The time evolution of the particle distribution function in phase space obeys the Vlasov-Poisson equations, but it is hopeless to solve these equations in the self-consistent manner. Even computer simulations are troublesome because any high-intensity beam consists of a huge number of interacting particles. In experiments, we also face many practical limitations due to the poor controllability of fundamental parameters in a large-scale machine. To overcome these difficulties in conventional approaches, the Beam Physics Group of Hiroshima University has developed a novel tabletop apparatus named “S-POD” (Simulator of Particle Orbit Dynamics). The S-POD is based on a compact linear Paul trap (LPT). According to the first proposal by Okamoto and Tanaka, a non-neutral plasma confined in a LPT can be made physically equivalent to a charged-particle beam traveling in an alternating-gradient (AG) focusing channel. We can thus use this compact system, instead of a large accelerator, to investigate the collective nature of intense beams. As shall be clarified in later sections, there are many practical advantages in S-POD experiments, compared with conventional accelerator-based experiments.

The present thesis addresses two separate topics of future importance; namely, coherent resonances near half-integer tunes in high-intensity hadron rings and resonance crossing in non-scaling fixed-field AG accelerators

(NS-FFAG). The S-POD is applied to explore these issues systematically. After a brief introduction in Chapter 1, we first outline the standard beam-orbit theory in Chapter 2 for later convenience. Chapters 3 and 4 are devoted to the description of the LPT and other S-POD components. The principle of S-POD experiment as well as how to operate the whole system are explained in detail. We then proceed to the two major topics mentioned above. In Chapter 5, we show that the coherent instability of the dipole mode can be excited, in addition to the well-known quadrupole resonance, near every half-integer tune per lattice superperiod of a storage ring. Both instabilities appear side by side or overlap each other, but are mostly separable because the dipole resonance often creates a narrower stop band accompanied by more severe particle losses. The separation of these low-order resonance bands becomes greater as the beam intensity increases. The S-POD system is employed to experimentally demonstrate the parameter-dependence of the double stop-band structure. Numerical simulation results obtained with a particle-in-cell (PIC) code are also given in this chapter to support our interpretations of experimental data. Finally, in Chapter 6, we make an extensive study of resonance crossing with the S-POD, assuming the lattice condition of the EMMA accelerator constructed at the Rutherford Appleton Laboratory in England. Emphasis is placed upon the integer-resonance crossing that may give rise to serious trouble in general NS-FFAGs. The theoretical prediction of the coherent excitation of dipole motion is experimentally verified over a wide range of machine errors and crossing speeds. In addition, the cancellation of amplitude growth dependent on the relative betatron oscillation phase between two consecutive resonances is observed and studied. We also explore nonlinear effects and, in particular, the effects of amplitude-dependent tune shifts and find that these nonlinear effects are a key factor in understanding our experimental results.