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Summary

"Wide-band acceleration and barrier bucket beam handlings in the induction synchrotron"

Since the invention of accelerator at the beginning of the 20th century, so many accelerators has been built and dedicated to the progress in science and technology, especially on the cutting edges of modern particle physics. In the accelerator history, one of the most important inventions is the synchrotron independently invented by Vladimir Veksler and by Edwin McMillan in 1945. It is a circular machine that can produce high energy beams efficiently. The succeeding prominent invention is the principle of strong focusing which was conceived by Nicholas Christofilos in 1949 and found by Ernest Courant, M. Stanley Livingston, and H. Snyder at Brookhaven National Laboratory in 1952 without recognizing the work of Christofilos. The third one is that of separate-function strong-focusing invented by Toshio Kitagaki, which takes a crucial role to realize flexible accelerators such as various synchrotron radiation source or colliders.

There are two streams in the frontier of modern synchrotron; one stream is the energy frontier such as Large Hadron Collider (LHC) in the European Organization for Nuclear Research (CERN) and the other is the intensity (or luminosity) frontier such as Japan Proton Accelerator Research Complex (J-PARC) or Super-KEKB in Japan.

In the case of pursuing maximum energy, an accelerator equipped with RF cavities with a higher quality factor, which can produce their maximum RF voltages, is designed. In the case of desiring maximum beam intensity, RF cavities with a lower quality factor are adapted. Modern hadron machines are just the case. This comes from a fact that low Q cavities can generate a larger beam bucket to accommodate a beam in the phase space of time and energy. From these reasons, frequency band widening of RF cavity or development of a low Q cavity have been a big concern of the accelerator society since 1983.

A typical example of wide-band RF cavities employs the Magnetic Alloy (MA). It is unnecessary in this system to control the cavity inductance so as to generate a desired RF frequency because of its wide-band characteristic. This technology is now popular as "non-synchronous acceleration". For the first time, Ninomiya of KEK proposed this method in 1989 and succeeded to demonstrate it in the late '90s. The RF group of J-PARC Rapid Cycling Synchrotron (RCS) succeeded to reduce Q factor to 2 and the RF cavities are dedicated to the actual high intensity operation.

Under the current trend of pursuing low Q RF cavity, the induction synchrotron (IS) has been invented in 2000. This induction synchrotron (IS) is regarded as a synchrotron operated with extremely wider RF frequency. A super-wide beam bucket is created there, avoiding the difficulty in the superimposition of Fourier components in the RF synchrotron as written in Chapter 2. The IS employs an induction cells of 1-to-1 pulse transformer as an acceleration device, which has been long used for an induction linac. In the context of traditional RF accelerator technology, the induction cell is characterized by its nature of super-wide-band of the quality factor less than 1 as introduced in Chapter 2. It can directly produce rectangular acceleration voltage pulses.

The concept of the IS was originally invented by Takayama and Kishiro in 2000 and then a super-bunch hadron collider, which realizes an extremely long bunch of 1 μs in the so-called barrier bucket, was proposed in 2002. After the extensive R&D works on the switching power supply energizing the induction cell, the proof-of-principle experiment of the IS was successfully carried

out using the KEK 12 GeV PS in 2007. The concept of all-ion accelerator was proposed in 2007, which allows acceleration of all species of ion with their possible charge states due to the characteristics of extremely wide-band, in other word, no limitation in the frequency band-width. The same group has developed the KEK digital accelerator as an all ion accelerator, which is a small fast cycling IS. The KEK digital accelerator is the renovation of the former KEK 500 MeV booster ring.

The IS provides three notable acceleration capabilities. The first is the “wide-band acceleration“, in which a low energy beam can be accelerated up to energy allowed by the maximum magnetic flux density of the guiding magnet in a single synchrotron. It does not require an expensive and large-scale injector such as Radio-Frequency Quadrupole (RFQ) and drift-tube linac. The beam revolution frequency is allowed to change in two orders in one acceleration cycle. This technology has another aspect of all ion acceleration as mentioned above. Various ion species with different mass to charge ratio including cluster ion can be accelerated by this method. The second is "novel beam handling" by the state of art use of the barrier buckets. The longitudinal beam compression, expansion, splitting, and merging are among them. The third is the “super-bunch acceleration” with asymmetric rectangular acceleration pulses. Although this induction acceleration technology in a circular ring has still unsolved problems such as beam loading compensation for a high intensity beam, the super-bunch operation even in the KEK digital accelerator is possible when the beam intensity there is reduced to low level.

Although the induction synchrotron has been considered to have above unique and useful aspects, they have not been comprehensively, especially experimentally explored. For the purpose to fully manifest its capability, this thesis work has been conducted. The results should be beneficial for future ideal induction synchrotrons. In this dissertation, wide-band acceleration technologies and their possibilities in the KEK digital accelerator have been studied by means of experimental and numerical tools.

This construction of the thesis is as follows.

Chapter 2 gives general properties of induction synchrotron. It establishes voltage separation of confinement and acceleration functions. Three super-wide-band technologies are derived from the impedance characteristic. Preceding studies for various induction acceleration systems for arbitrary pulse generation by Linear Transformer Driver (LTD) and asymmetric pulse generation are also described.

Chapter 3 provides the overview of the KEK-DA which is a small prototype of induction synchrotron. This machine specifications and limitations are introduced in detail. As the author contrived, several methods about typical beam information such as transverse beam sizes and initial momentum spread using acceleration voltages are explained.

Chapter 4 explains the wide-band acceleration technology of induction synchrotron which can accelerate heavy ion beams within some wide-band frequency with experiments. This is an intermittent-turn acceleration scheme called the pulse density control because of the combination of fixed heights of induction accelerate voltage and fast cycling characteristic of the KEK-DA. This experiment has demonstrated successfully and also compared to simulation results, which has well reproduced it and revealed the mechanism of longitudinal emittance blow-up at the initial acceleration stage.

In Chapter 5, super-bunch acceleration technology is discussed for the upgraded KEK-DA. It can not only accelerate long beams with asymmetric induction pulses but also resolve the problems about initial longitudinal emittance blow-up and synchro-beta coupling caused by the combination of the present KEK-DA optics and setups. The key technology is a time-variable induction system which can always provide required acceleration voltage. The result of its SPICE model shows such a system is acceptable and can stably produce asymmetric pulses for super bunches under the condition of ignoring beam loading effects.

In Chapter 6, typical beam handling technologies are introduced with barrier buckets with experimental results. In the first section, several barrier buckets schemes which have been carried out for other facilities in the world are introduced. The author has proposed new beam handling method, fast beam compression scheme which saves its manipulating time without large emittance blow-up. The second is about fast beam rotation method for beam splitting and merging in longitudinal phase space. Both of them have been demonstrated experimentally and shown their capabilities.

Chapter 7 summarizes and concludes and the studies in this thesis. A brief discussion about the future possibilities is discussed.