論文の内容の要旨

Development of a Transmission Electron Microscope Adopting Two-Mode Superconducting RF Accelerating Cavity for Achieving Low Energy Dispersion

(低エネルギー分散を実現する 2モード超伝導加速空洞を採用した 透過型電子顕微鏡の開発研究)

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This doctoral thesis reports the development and the study about the overall system design and the fundamental technologies for the world's first application of superconducting radio frequency (SRF) technology to a transmission electron microscopes (TEM).

A TEM is a vital tool to image sub-nanometer structures of specimens. It has been utilized in a wide range of fields including material science and biology. It is necessary to process specimens into layers as thin as a few tens of nm for the present TEM with the accelerating voltage of a few 100 kV. This is because the imaging power with high spatial resolution cannot be realized for thicker specimens as a consequence of the energy loss of the electron beam due to inelastic scatterings with the specimen and the decrease of the electron beam flux due to scatterings including elastic ones.

Recently a project that aims to adopt various technologies developed for high-energy accelerators into TEM is being carried out at High Energy Accelerator Research Organization (KEK) in Tsukuba, Ibaraki, Japan. This employs Radio Frequency (RF) resonant cavity which can generate accelerating fields as high as a few 10 MV/m in order to realize a new type of TEM with higher accelerating voltage than ever. Moreover superconducting RF cavity is adopted so that a high beam current comparable with conventional TEMs can be acquired and the accelerating field can be controlled more precisely than normal-conducting cavities. This new type of TEM, superconducting RF transmission electron microscope (SRF-TEM) is expected to enable the observation of thicker specimens than ever owing to its high accelerating voltage.

The SRF-TEM is capable of realizing a significant increase in e^- beam energy with a reasonably compact facility. However, the RF acceleration scheme generally used in high-energy accelerators causes larger beam energy dispersion which degrades the spatial resolution of the TEM. In this study, a new type of accelerating cavity named “two-mode cavity” in which two oscillating accelerating fields coexist was developed. The two-mode cavity is capable of flattening the sharp peak of the accelerating RF wave by superimposing one resonant mode of TM_{010} whose resonant frequency is 1.3 GHz on its double resonant mode of TM_{020} (2.6 GHz). A photocathode electron gun that is already developed is

introduced into the SRF-TEM instead of a thermal electron or a cold field emission gun normally used for a conventional TEM. This can generate ultra-short bunches of a few ps and supply electron bunches precisely synchronized to the period of the accelerating field of the two-mode cavity. This is also expected to provide the good time resolution to SRF-TEM.

In this thesis, I describe the overall system design of the SRF-TEM and the establishment of the essential technologies for the SRF-TEM with 300 kV as a proof-of-principle prototype and a future 3 MV SRF-TEM. As the system design, we confirmed that the two-mode cavity can achieve low energy dispersion for the SRF-TEM with 300 kV and 3 MV by beam dynamics simulations.

Essential technologies are 1) the two-mode cavity which can generate the high accelerating gradient of about 10 MV/m with two resonant modes of TM_{010} and TM_{020}, and 2) the RF feedback system which can control the accelerating fields generated in the two-mode cavity precisely; (0.0012 ± 0.0003) % in terms of amplitude and (0.04 ± 0.01) mdeg. in terms of phase for the TM_{010} mode and (0.0005 ± 0.0004) % and (0.03 ± 0.01) mdeg. for the TM_{020} mode.

With the above, we opened up the road to the fully new TEM, SRF-TEM.