Design and Numerical Analysis of a Coherent Electron Resonator for the Quantum Electron Microscope

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The quantum electron microscope (QEM) is a proposed EM modality to reduce the radiation damage of sensitive samples[1]. In the recent years, an international collaboration has been leading the efforts to implement practical designs for QEM. As of now, these designs are composed of three unique electron optical elements: (1) resonator: an element that enables the electron beam to travel in a periodic fashion, (2) two-state coupler: an element to split (couple) the electron beam into (between) the reference and sample beams, and (3) a "barn door": a time-dependent system to couple the beam into the resonator.

Here, we focus our efforts on a design which can be integrated with an existing scanning electron microscope for the proof-of-concept of a coherent electron resonator (Figure 1). To achieve periodic behavior in our resonator design, we use a diffractive mirror as the two-state coupler, which can reflect and diffract the electron beam simultaneously. The barn door acts as an electron mirror when closed, allowing electrons to travel back and forth in the resonator. We calculated electrical fields and simulated electron trajectories for reference and sample beams (Figure 2).

In order to obtain electron optical properties such as aberration coefficients and beam spot with a high accuracy, we developed a solver using an automatic differentiation (AD) technique. AD provides a straightforward way to get the aberration coefficients without deriving them in advance and its accuracy is up to machine precision[3]. A spline function interpolation was used to get the spatial field and its arbitrary derivatives due to the high stability[3]. Aberration coefficients and beam radius of reference and sample beams in the resonator were obtained through ray-tracing with fourth-order Runge-Kutta method. Coefficients of spherical/ chromatic aberrations and beam diameter were calculated when the reference beam was focused at the focal point on the flat potential of the barn door. Furthermore, we characterized electron optical properties as a function of repetition (roundtrips).

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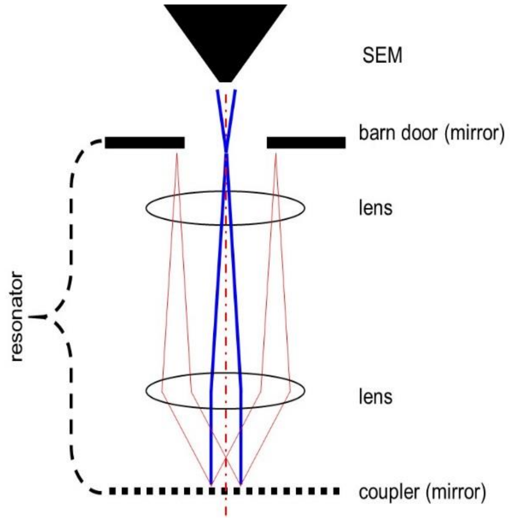

Figure 1: Schematic diagram of QEM, designed to be integrated in an existing SEM. The resonator was composed of barn door and coupler (diffractive electron mirror). After the electron beam enters into resonator through the barn door, the barn door acts as the electron mirror. Blue and red rays represent the reference and the sample beam, respectively. Two lenses were placed in front of the barn door and coupler. Blue ray and red ray represent the reference and sample beam, respectively.

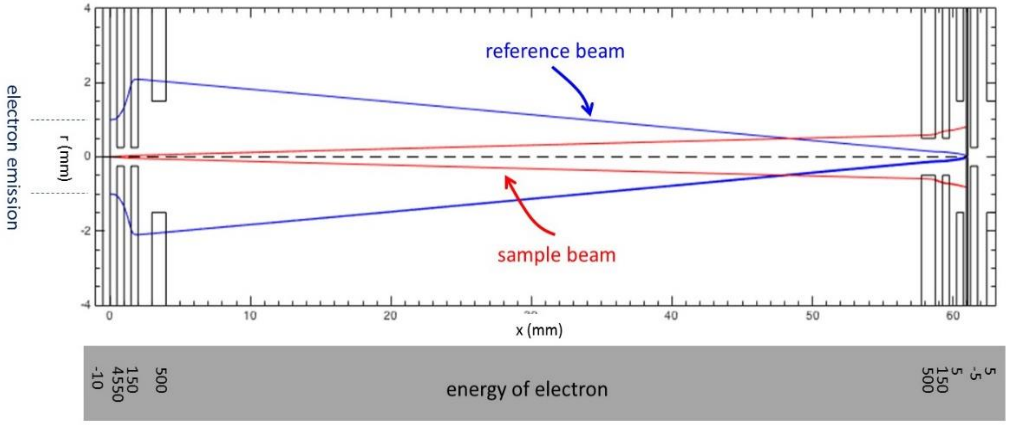

Figure 2: 60 mm-scale design of QEM with *Lorentz-2E* (Integrated Engineering Software Inc.). The diffractive electron mirror was treated as a flat mirror because Lorentz-2E cannot model any effects related to De Broglie's wavelength of electrons. In order to simulate repeated bounces of zeroth beam and ±first order diffracted beam from grating mirror, the reference and sample beams were emitted separately from the left side of the electron resonator. The reference beam was emitted where r = 50 µm with the angle of 0 *rad*, and the sample was emitted where r = 0 with the angle of ±10 *mrad*. 500 *eV* of electrons were emitted near the grating mirror side (left) in two different position and angle for the reference (blue) and sample (red) beams, and electron trajectories of both beams in the resonator were calculated. The variation of energy of electron along z-axis is shown at the bottom. Here, the r-axis was scaled up by 20 for the visualization of two different electron trajectories.