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Ultrafast Electron Microscope Column Design: An Efficient Semi-analytical Approach

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Ultrafast electron microscopy (UEM) promises to combine the sub-nm spatial resolution of electron microscopy with the sub-picosecond temporal resolution of modern short-pulse lasers, thereby providing an invaluable new tool for materials science, biology and chemistry [1]. Key to the design and development of such high space-time resolution instruments is access to an accurate simulation of the electron pulse propagation in the microscope column. Here, we present an efficient semi-analytical approach to UEM column simulation based on the analytical Gaussian (AG) model of Michalik and Sipe [2], which employs six parameters (pulse size, local momentum variance and chirp in the transverse and longitudinal directions) to determine electron pulse propagation dynamics due to dispersive and global space-charge effects. We have modified this efficient, yet accurate [3], model to allow for the inclusion of the action of external forces on the electron pulse due to column elements such as magnetic lenses and RF cavities [4].

Figure 1 depicts an example 100kV UEM column design optimized for the delivery of the shortest possible electron pulse at the focal spot on the specimen. The initial electron pulse parameters at the surface of the photocathode are determined by careful analysis of the laser-driven photoemission process; in this case, a Ta photocathode irradiated by a 100fs duration, 261nm (an excess photoemission energy of 0.5eV) UV laser pulse with a spatial diameter of 0.2mm. Propagation though the acceleration region in the DC photogun employs the electric field distribution evaluated from a finite-element analysis of the gun design [5]; that is, the simulation includes the effect of the non-uniform field distribution in the gun (e.g., anode lensing). A 3GHz TM_{010}-mode cylindrical 'pill-box' RF cavity positioned in the center of the ~40cm gun-specimen column distance is used to 'temporally' focus the electron pulse at the specimen position. Two magnetic lenses either side of the RF pulse compression cavity compensate for both the intrinsic spatial beam divergence and the *negative* RF cavity lensing. For the presented example, their focal strength is adjusted to produce the spatial momentum distribution (Fourier plane) at the front focal plane of the microscope's f = 5mm objective lens. This then allows an aperture to be used to select a reduced transverse beam divergence. For the 100μm-diameter aperture employed in Figure 1, the resulting beam 'clean-up' generates a ~1μm focal spot size on the specimen – a spot size that would allow ~1nm spatial imaging resolution using a 1k× 1k CCD detector to collect all the electrons in a TEM geometry.

The basic UEM column design presented in Figure 1 can be employed in other operational modes. In particular, the field strength in the RF cavity can be reduced to effectively null the temporal electron pulse dynamics, thereby producing a pulsed electron source with a minimized energy width (ΔE < 0.1eV) ideal for ultrafast EELS studies. Alternatively, the strength of the magnetic lenses around the RF cavity may be increased to facilitate a larger electron current throughput to the sample, at the expense of an increase in the objective's focal spot size. Of course, space-charge effects will also influence the attainable electron column throughput and space-time focus. Such effects and the limitations of the model will be discussed.

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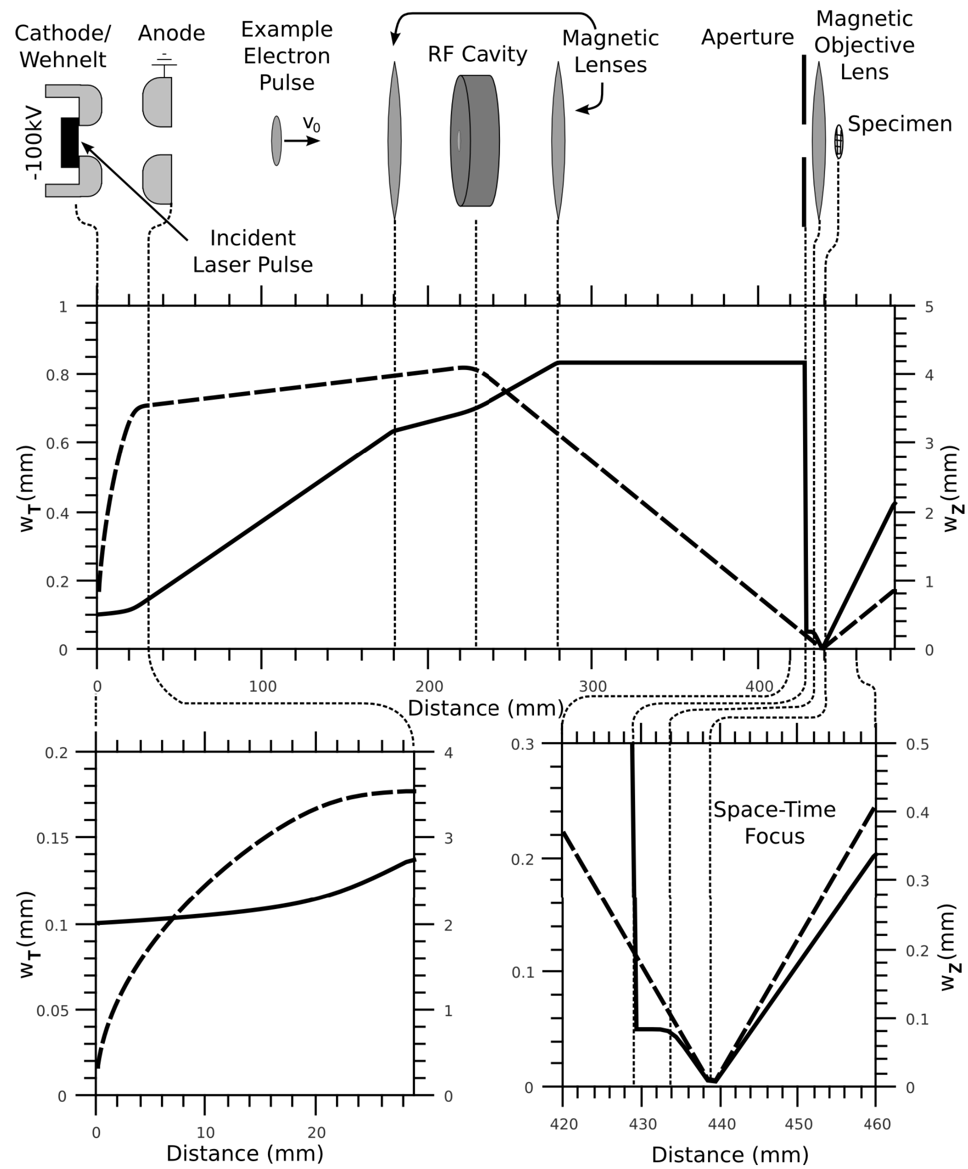

FIG. 1. Propagation dynamics of an ultrashort electron pulse in a 100kV UEM column: Transverse (*T*, solid line) and longitudinal (i.e., temporal) (*z*, dashed line) half-width 1/e maximum (*w*) pulse widths after photo-generation by a 100fs laser pulse of 0.2mm diameter. Bottom: Details of the DC gun acceleration region (left) and the space-time focus at the specimen (right).

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