

Developing a Next Generation Ultrafast Electron Microscope

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Introduction

Since its conception in 1937, electron microscopy has given us an insight into the molecular and atomic worlds, unobtainable through traditional photonic imaging methods. Through the work of de Broglie, electrons have an energy dependent wavelength allowing for an increased resolution compared to the photonic microscopy counterpart.

The advent of the femtosecond laser now means that electron microscopy is not limited to atomic scale spatial resolution; it opened the door for imaging on atomic time-scales. Through the photoemission process femtosecond pulses of electrons can be generated and used in the pump-probe regime.

Using Nanoscale Metal Tips (NSMT) provides an emission site with a radius approximately 50 nm, ensuring high transverse coherence and a naturally divergent beam [1,2], hence making them an ideal candidate for Point Projection Microscopy (PPM), which requires a spherical wave incident on the sample and gives a real space image of the sample. Collimating this spherical wave front allows for Coherent Diffractive Imaging (CDI), which gives a reciprocal space image of the sample.

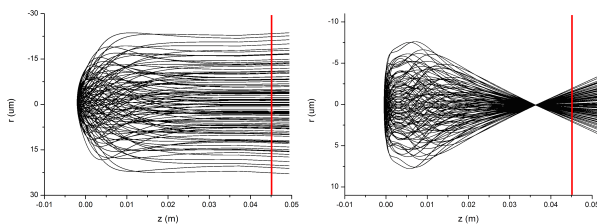


Fig 1: An example of the different operational modes of an idealized femtosecond electron microscope. The red line indicates the sample location. (Left) Shows a collimated bunch incident on the sample, suitable for CDI. (Right) Shows a divergent wave front at the sample, suitable for PPM. As the magnification of a PPM image is given by the ratio of the source-detector and source-sample distances, and as the source of the divergent wave front can be defined as the focus of the beam, having a tunable focus also gives tunable magnification.

To observe dynamics within a nano-scale structure the electrons require an appropriate Inelastic Mean Free Path (IMFP), a quantity dependent on beam energy. Typically 10s of keV are required (a 25keV electron has an IMFP of 21nm in copper), comparable to traditional Transmission Electron Microscopes (TEMs). However, in TEMs the flight path is of the order of a meter, during which multiple lenses focus and correct the beam. This is problematic when trying to keep the temporal profile of the electron bunch to a minimum due to broadening effects such as space charge, geometric broadening and energy broadening.

Pulse Broadening

Operating in the single electron per shot regime, which has been verified experimentally, means space charge effects can be negated and is assumed throughout (see article by W. Bryan). Geometric broadening arises from path length differences between off-axis and on-axis electrons. Energy broadening is an intrinsic part of the photoemission process, resulting from the bandwidth associated with the incident laser pulse carrying through to a spread of electron energies and hence arrival times.

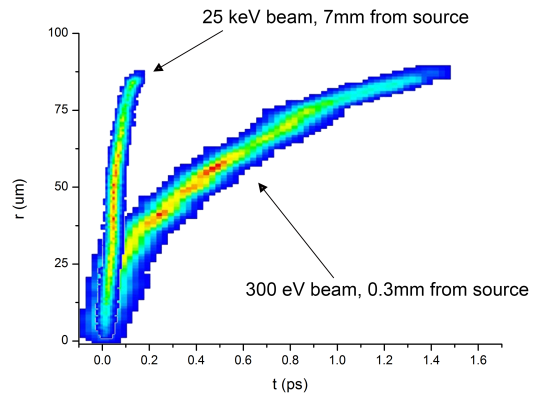


Fig 2: An illustration of the influence of geometric broadening. Shown are the distributions of two pulses overlaid on the same time-scale. The spherical wave has propagated 0.3mm from source with a beam energy of 300eV. The collimated beam has propagated 7mm from source and has a beam energy of 25keV. Allowing the beam to diverge naturally has extended the temporal profile of the bunch to 1.5ps. Catching the beam before it naturally expands is essential in reducing geometric broadening.

Novel Femtosecond Electron Microscopy Concept

To combat these broadening effects the manipulation and acceleration of the electron bunch is done simultaneously. This requires a lens in close proximity to the emission site, as to prevent unwanted divergence of the bunch and therefore reduce geometric broadening. This also has the advantage of allowing for an ultra-compact design which reduces the temporal stretching due to the energy bandwidth as the time of flight can be reduced.

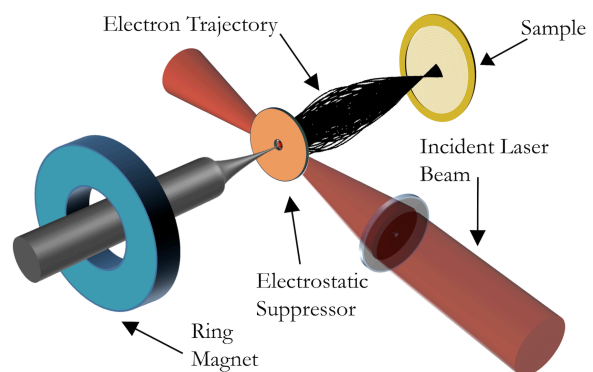


Fig 3: Example experimental layout. Placing the lens behind the emission site allows for not only the reduction of geometric broadening, but allows for the source – sample distance to be limited by electrostatic breakdown, giving the short temporal profile of the bunch as required. The variable position Neodymium ring magnet gives a tunable B field, making both CDI and PPM achievable within the same experiential configuration. An electrostatic suppressor [3] gives control over the radial expansion of the bunch by flattening the electrostatic field in the vicinity of the NSMT.

Simulations

Simulations were conducted on the Poisson Superfish software package [4], which includes Automesh, Poisson and Pandira. Geometries were constructed on Automesh, which gives the interpolation framework for the field solvers (Pandira for magnetic, Poisson for electrostatic). These field maps are converted, and then loaded into the General Particle Tracer (GPT) [5], which allows for the input of beam parameters and provides a detailed trajectory analysis. Using the GPT single loop solenoid function, an investigation was conducted looking into the required field strength for a given solenoid position.

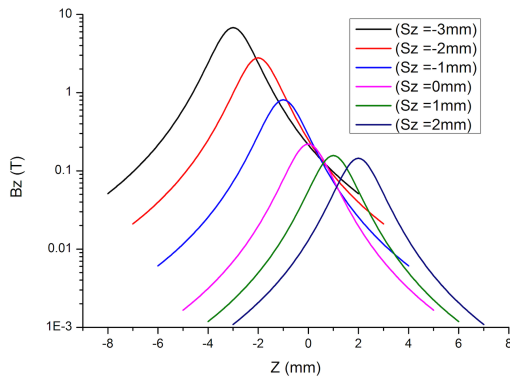
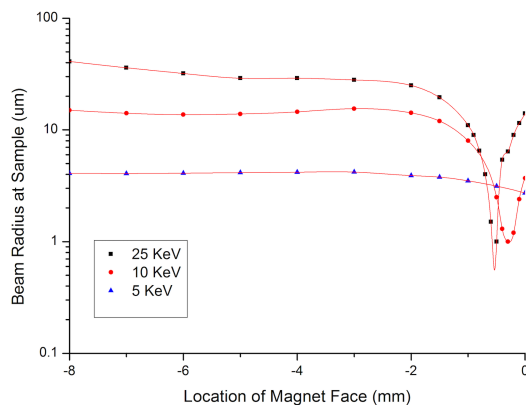


Fig 4: Assuming the NSMT apex is located at $z=0$ mm, the on axis B field distribution required to collimate a 25keV electron pulse are presented.

As shown in the above figure, the required field strengths would require superconducting coils, unnecessarily adding to the experimental complexity. The permanent magnet ring was therefore chosen as a viable alternative. Similarly to fig 4, the magnet position was scanned across various positions, terminating at $z=0$ mm. As horizontal laser access to the emission site is required there are spatial bounds on the position of the lens.



The beam radius in the sample plane was simulated as a function of magnet position for a variety of beam energies. Location of the magnet face describes the face closest to the apex of the NSMT. It is shown that only the higher beam energies are applicable for use with this magnet geometry, as a focus is achieved within the appropriate range of magnet positions. Collimation of the bunch occurred with the magnet placed at 5mm, 3mm and 0mm for beam energies of 25keV, 10keV and 5keV respectively.

Beam energies ranging from 10 to 30 keV were found to be focusable using a commercially available neodymium ring magnet, as displayed in fig 5. As the strength of the tangential component of the Lorentz force exerted by the lens on the bunch is dependent on the axial and radial components of the electron velocity (as well as the strength of the radial and axial components of the B field itself), and as the radial focusing force is dependent on this induced tangential velocity, the lower

beam energies (hence lower axial and radial velocity components) require stronger B fields, or an increased exposure time in a weaker B field. Interchangeable ring magnets of varying geometries and strengths would allow for a wider variety of beam energies to be focused within the acceptable range of lens positions. The introduction of a pole piece surrounding the magnet would also grant further flexibility in tuning the strength of the B field and allow for a wider range of beam energies to function given a specific magnet geometry or strength.

Conclusions

This work indicates that a new operational mode of femtosecond microscopy is experimentally possible, allowing for both diffractive and real space imaging over a variety of beam energies. Investigations into a range of experimental geometries are currently being conducted, as well as looking into the engineering aspects of implementing such a system.

Acknowledgements

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