Advanced Extreme Ultraviolet Nanometrology for Imaging Function in Nanosystems

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Introduction

Advanced materials development and device design require characterization tools to discover, optimize and monitor new nanomanufacturing techniques. At the frontiers of nanofabrication, precise characterization of nanostructures and surfaces is necessary for understanding and harnessing the new capabilities of nanosystems.

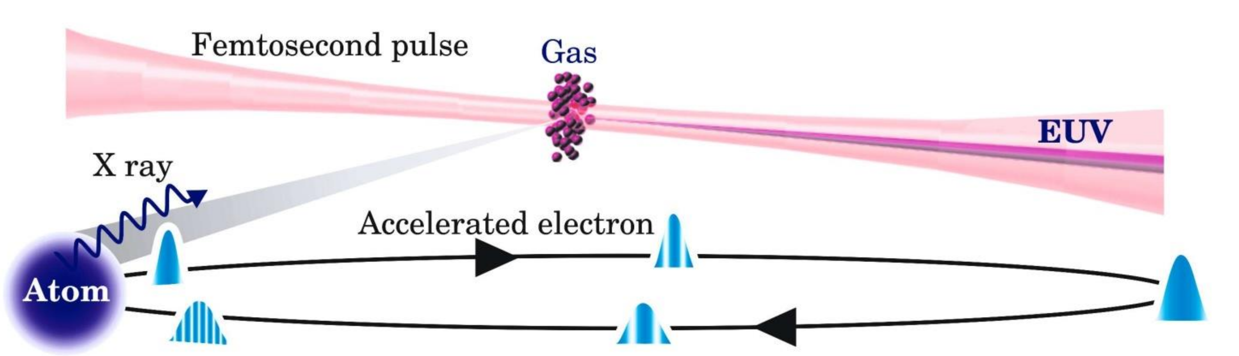
To probe the deep nano-regime, we use coherent extreme ultraviolet (EUV) high harmonic beams from tabletop femtosecond lasers. The shorter wavelength of EUV light can achieve near-wavelength-resolution 3D imaging of surfaces and is sensitive to picometer-scale displacements. In addition, the femtosecond duration of HHG pulses is fast enough to capture the fastest thermal, magnetic and acoustic dynamics relevant to function in few-nm scale structures.

In exciting recent work, we achieved a record spatial resolution of 40nm in tabletop full-field 3D imaging using an illumination wavelength of 30 nm. Moreover, we uncovered a new regime of collective heat dissipation that can improve thermal transport from closely-packed nanoscale hot spots. This new HHG light source, which now extends into the soft X-ray region, will enable new revolutionary applications for observing nanoscale systems on their intrinsic length and time scales.

High Harmonic Generation

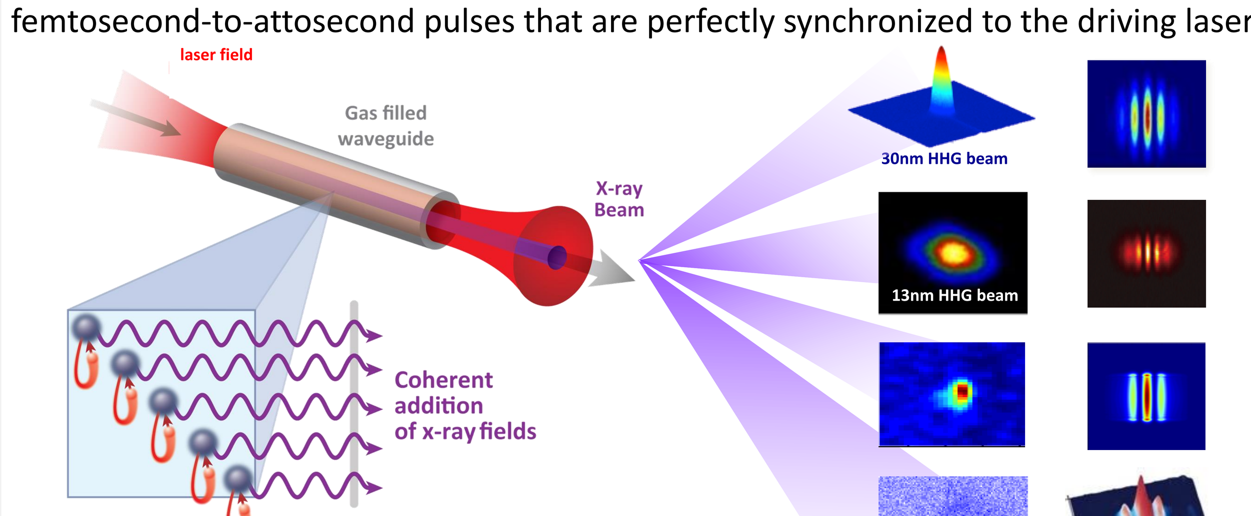
HHG — Nanoscale Radiating Antenna

In high harmonic generation, atoms undergo tunnel ionization in an intense laser field. The electron is accelerated in the laser field and when the laser field reverses direction, the electron is driven back to its parent atom The kinetic energy gained in the laser field is released in a high energy photon. Photon energies can reach into the extreme-ultraviolet (EUV) and soft-x-ray region, now with linear and circular polarization.



Generating Laser-Like High Harmonic Beams

To generate a bright high-harmonic beam, the upconversion process must be phase matched, where the HHG emission from many atoms combines constructively. We accomplish this by focusing the laser into a gas filled waveguide. By tuning the pressure in the waveguide, the dispersion from the neutral gas, free-electron plasma, and the geometric contributions from the waveguide combine so that both laser and HHG fields travel at the speed of light. This results in a fully coherent beam with femtosecond-to-attosecond pulses that are perfectly synchronized to the driving laser.



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*Kfir et al, Nature Photonics **9**, 99 (2015)*
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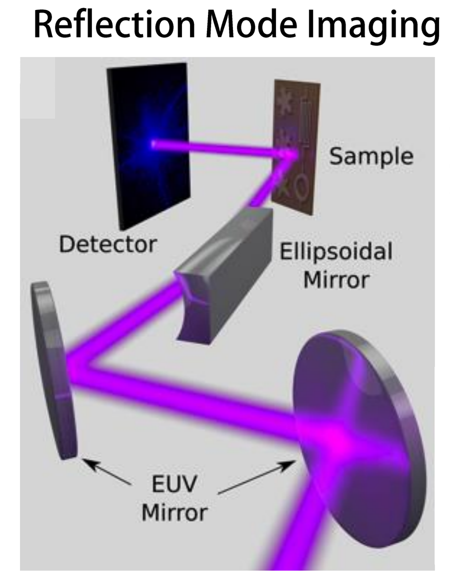
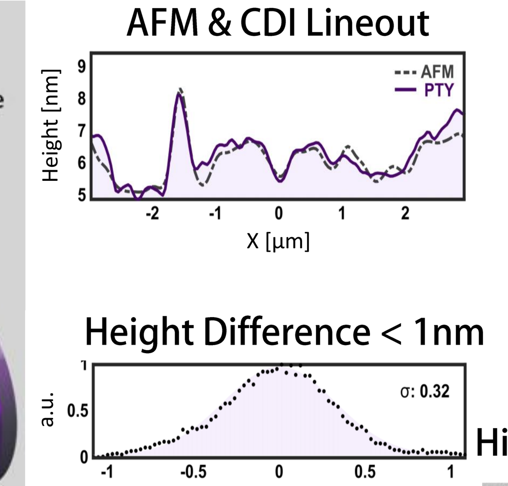
High Contrast 3D EUV imaging

Reflection Mode Imaging

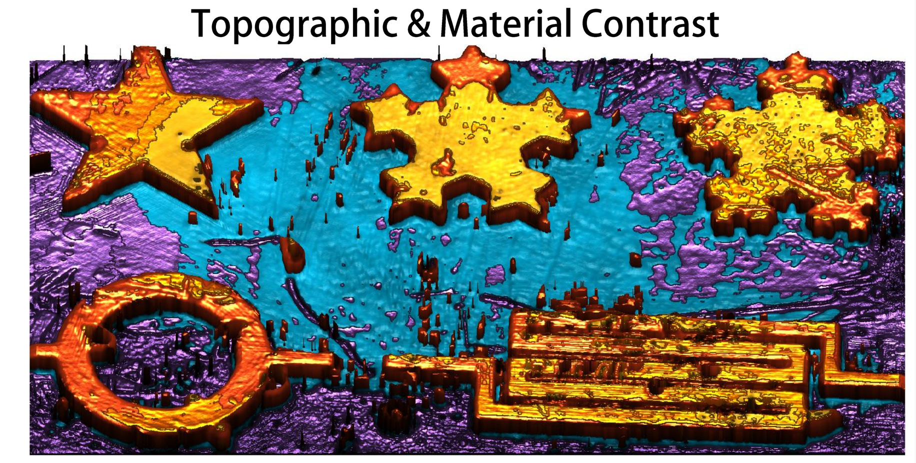


AFM & CDI Lineout

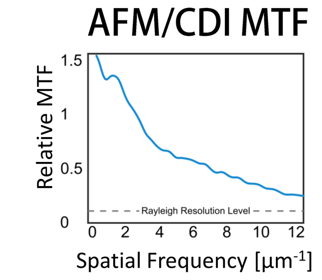
Height Difference < 1nm



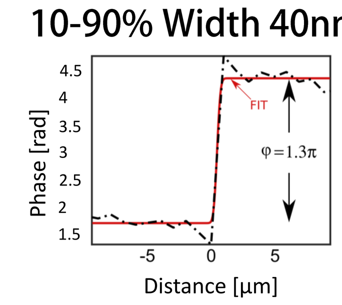
Topographic & Material Contrast



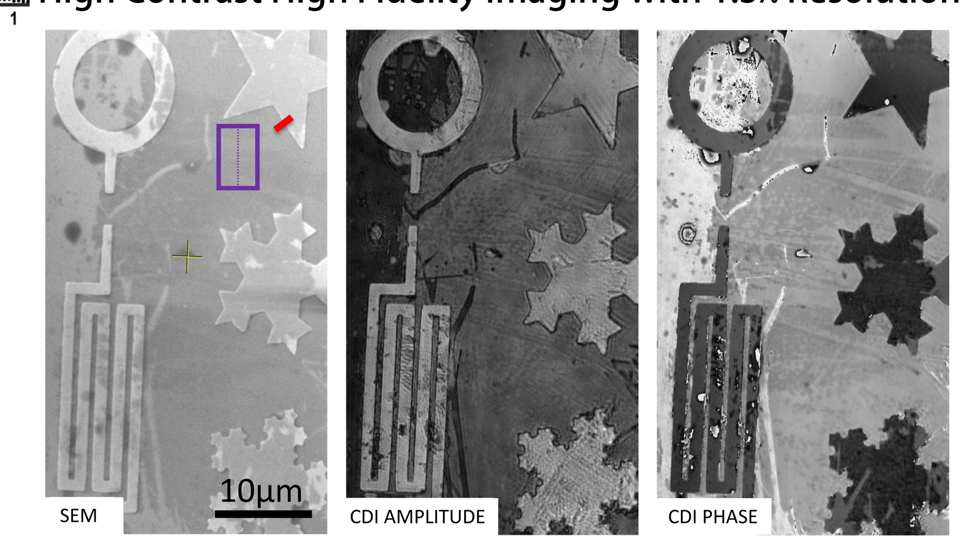
AFM/CDI MTF



10-90% Width 40nm



High Contrast High Fidelity Imaging with 1.3λ Resolution



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Zhang et al. Nanoletters (submitted);
*Seaberg et al. Optica **1**, 39 (2014);*
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*Gardner et al. Opt. Express **20**, 19050 (2012);*
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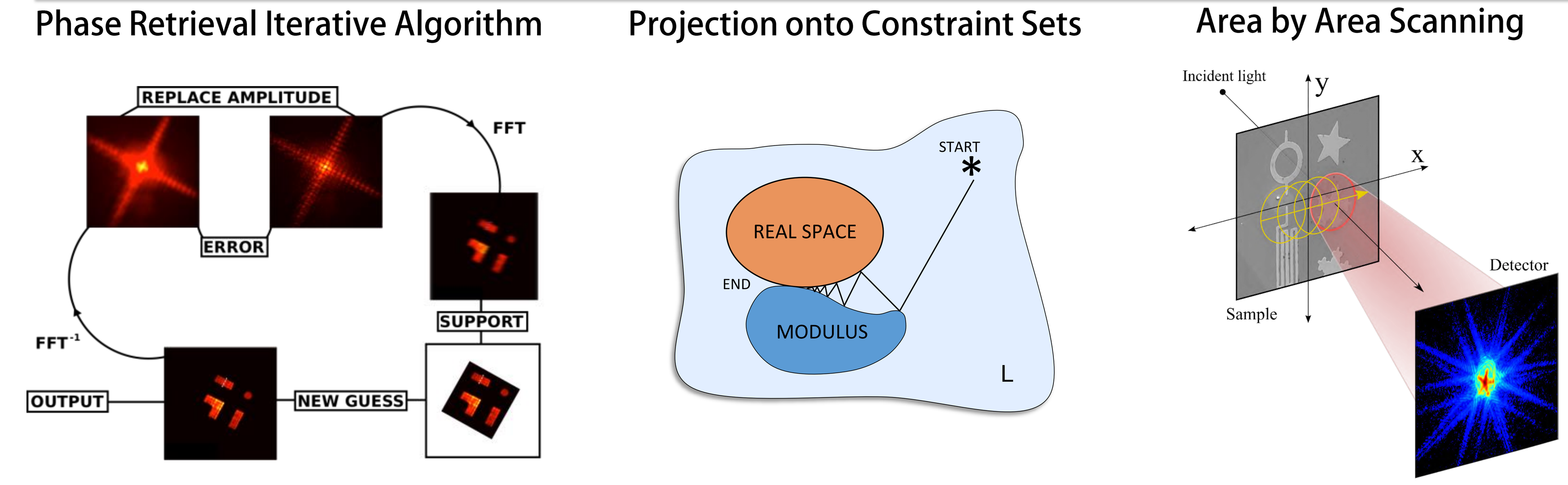
Two 45° angle-of-incidence multilayer mirrors select a single harmonic (30 nm), which is focused near the sample by an ellipsoidal mirror. The sample consists of titanium shapes patterned with e-beam lithography on a silicon substrate. The reconstructed amplitude and phase capture details of the slight surface variations. The amplitude and phase information is used to generate a 3D rendering of the surface topology. To characterize the spatial resolution, we calculate a relative modulation transfer function (MTF) from a higher resolution AFM image and measure the 10% to 90% width of an edge (red line in figure). Both support 40nm resolution (1.3λ). For the axial resolution, we can compare the calculated height from the phase, purple square, to an AFM measurement with the same spatial resolution. A lineout of the AFM and CDI height along the purple dash is shown. The difference histogram between CDI and AFM fits a Gaussian with a half width of 3.2 Å.

CDI Ptychography

Phase Retrieval Iterative Algorithm | Projection onto Constraint Sets | Area by Area Scanning



Coherent diffractive imaging (CDI) is a lensless full-field imaging technique that can achieve diffraction-limited spatial resolution. In CDI, a spatially coherent beam illuminates an object, and the intensity of the scattered light is collected on a detector. An iterative algorithm replaces any imaging optics by solving for the complex-valued map of the sample that satisfies both the measured data and one or more a-priori sample plane constraints. The resulting image contains quantitative amplitude (material composition) and phase (thickness/height) information. Ptychography CDI is particularly powerful because many diffraction patterns are collected from overlapping fields of view, rather than one diffraction pattern as in traditional CDI. This information redundancy provides a powerful constraint leading to high-fidelity, high-contrast images in both reflection and transmission-modes.

*Fienup. Appl Optics **21** 2758 (1982);*
*Maiden et al.. Ultramicroscopy **109**, 1256 (2009);*
*Adams et al. Opt. Express **20**, 24788 (2012);*
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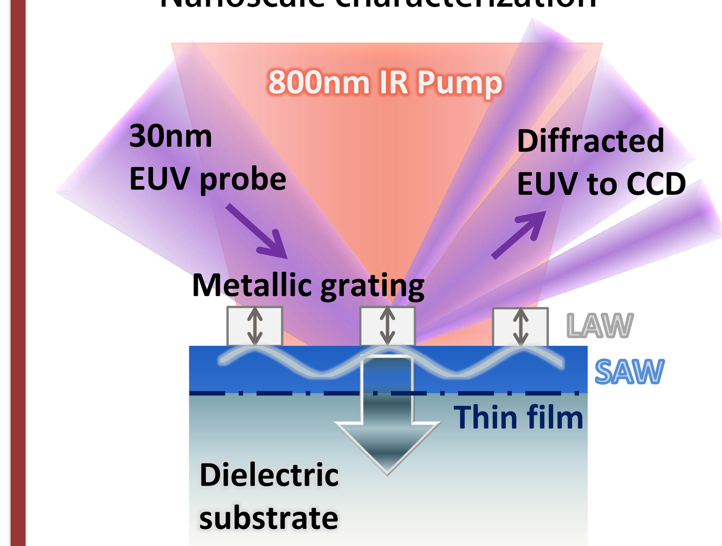
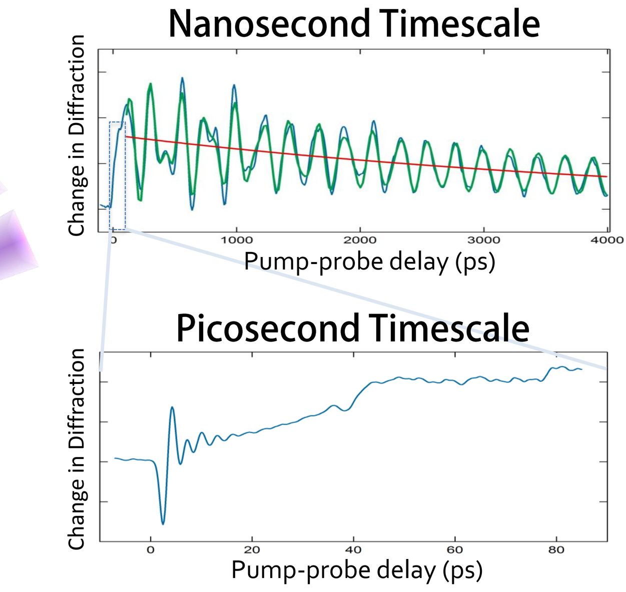
New Regime of Heat Flow

Nanoscale characterization



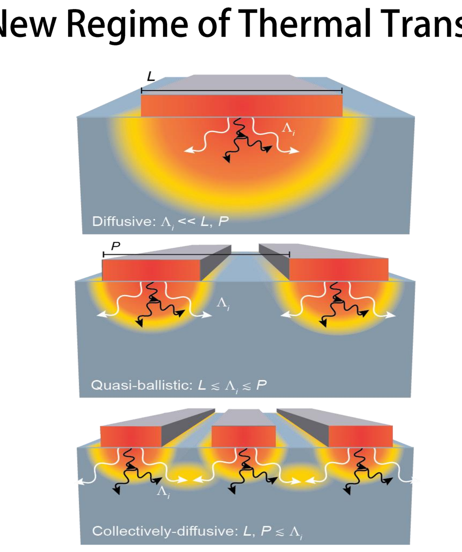
Nanosecond Timescale

Picosecond Timescale

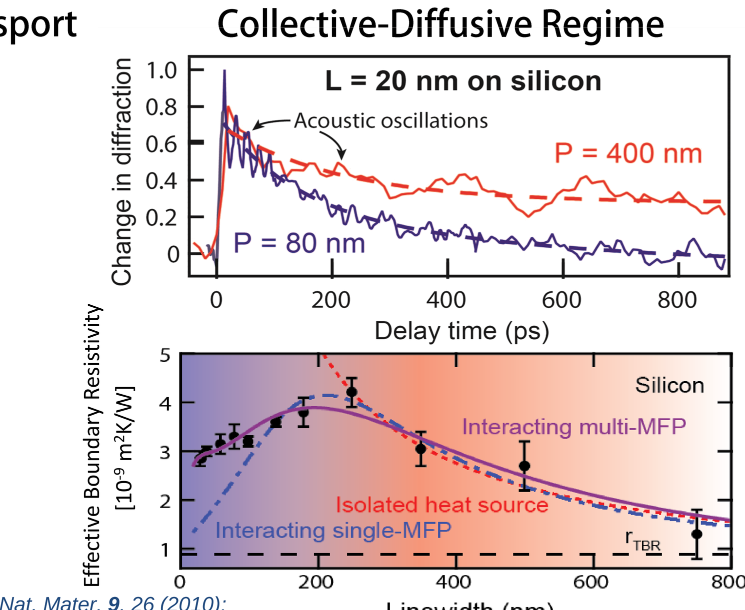


We focus an ultrafast laser onto a nano-patterned ultrathin film and substrate, causing thermal expansion and launching both surface acoustic waves (SAWs) and longitudinal acoustic waves (LAWs). EUV pulses probe the propagation dynamics of both SAWs and LAWs enabling the characterization of both Young's modulus and Poisson's ratio in a single measurements, as well as nanoscale heat dissipation rates.

New Regime of Thermal Transport



Collective-Diffusive Regime



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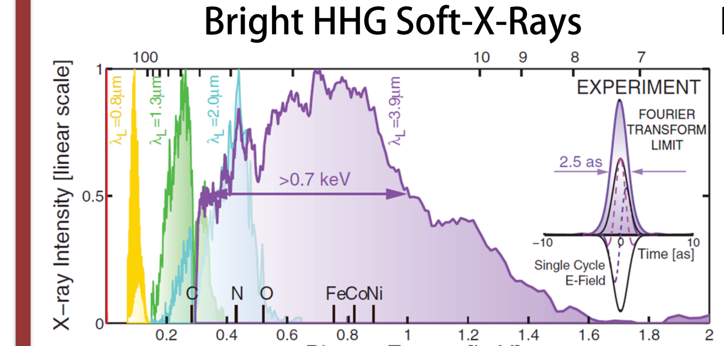
*Siemens et al., Nat. Mater. **9**, 26 (2010);*
*Li et al., PRB **85**, 195431 (2012)*

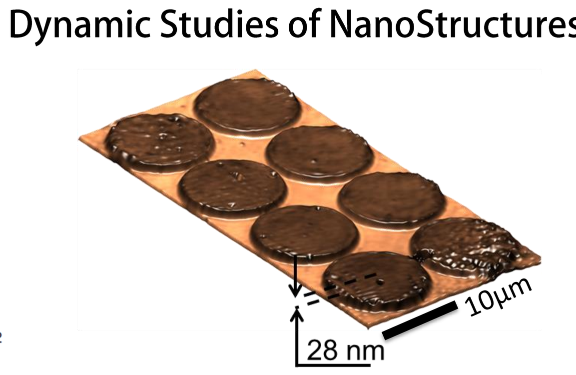
A complete description of nanoscale thermal transport is a fundamental problem that has defied understanding for decades. We uncover a surprising new regime of nano-scale thermal transport where, counterintuitively, nanoscale heat sources cool more quickly when placed close together than when they are widely separated. This increased cooling efficiency is possible when the separation between nanoscale heat sources is comparable to the average mean free paths of the dominant heat-carrying phonons. This finding suggests new approaches for addressing the significant challenge of thermal management in nanosystems, with design implications for integrated circuits, thermoelectric devices, nanoparticle- mediated thermal therapies, and nanoenhanced photovoltaics for improving clean-energy technologies.

Future Dynamic Imaging

Bright HHG Soft-X-Rays



Dynamic Studies of NanoStructures



Current HHG sources can reach sub-nm wavelengths with photon energies spanning many relevant element-specific absorption edges. Such wavelengths allow for element mapping, contamination detection and identification. HHG sources, with inherently ultrashort pulses, in combination with CDI techniques can capture the fastest charge, spin and phonon dynamics in nano-systems at the spatio-temporal limit.