Ultrahigh-resolution EUV Coherent Diffractive Imaging and Proposed EUVL Tools

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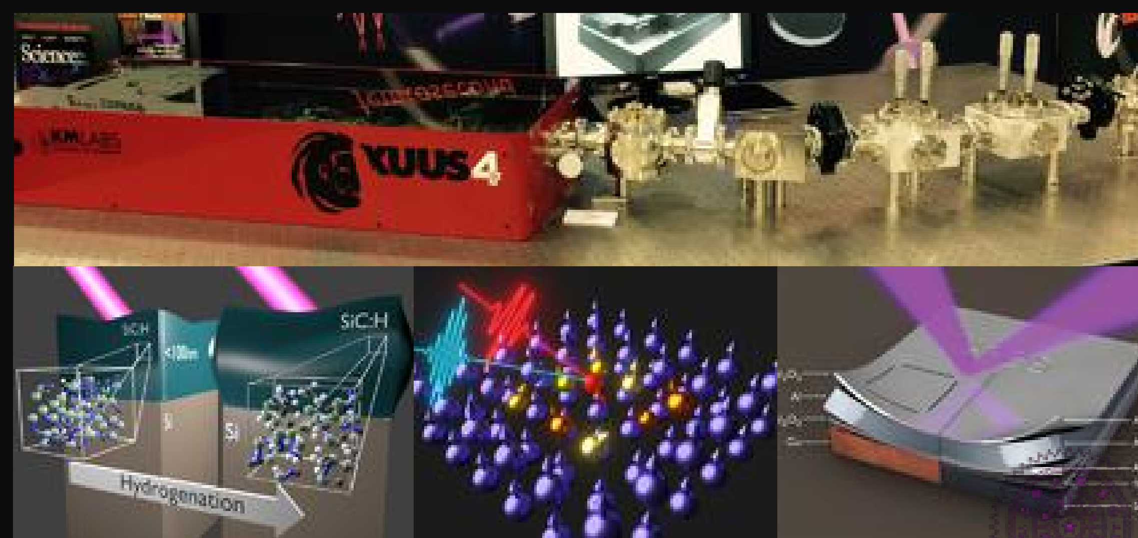
Dennis Gardner, Christina Porter, Elisabeth Shanblatt, Michael Tanksalvala, Robert Karl, Charles Bevis, Daniel Adams, Giulia Mancini

JILA and KMLabs



VUV/EUV/SXR **Metrology** **ARPES** **Imaging**

KMLABS inc. LEADING IN ULTRAFAST

JILA NIST CU

Outline

- **Advances in VUV/EUV/soft X-ray harmonics**
  - Control over spectral, temporal & polarization state
  - Integrated engineered systems in VUV, EUV
  - Ready for metrology: VUV-EUV

Y-Fi™ VUV

- **Harnessing spatial coherence of HHG**
  - 1st sub-wavelength full-field EUV imaging: record @ 13.5nm
  - Quantitative elemental/chemical maps
  - Buried layer imaging

- **EUVL Tools based on high harmonics**
  - Mask inspection: CDI-based mask review microscope is faster, cheaper than Zeiss AIMS®
  - Materials characterization: dopant profile, thin film metrology, sub-surface imaging, photolectron spectroscopy for in-situ materials growth, photovoltage spectroscopy

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Applications relevant to EUVL

Precise machining/material modification using fs fiber laser

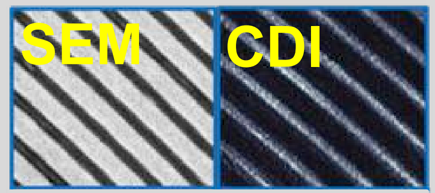
- Surface or sub-surface
- Cleaner cuts with fs
- Soft/hard materials
- Deep trenches

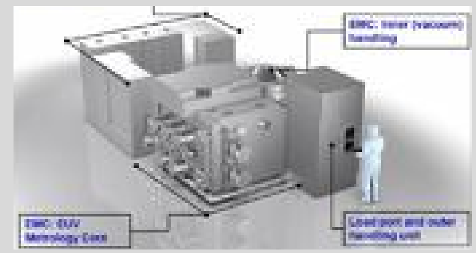
Patterned/bare wafer inspection

- Coherent laser-like beam
- Adjustable wavelength (DUV, VUV, EUV)
- Adjustable penetration depth
- Adjustable polarization (linear to circular)
- Quantitative elemental, chemical mapping
- Ultrasensitive to contaminants, roughness

Mask inspection @ 13.5nm

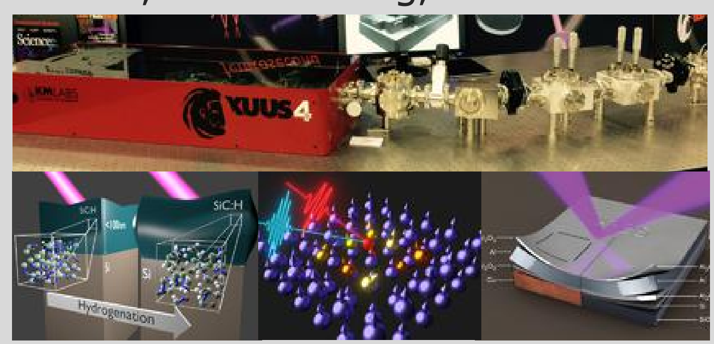
- Coherent beam -> higher resolution (<12.6nm)
- Wavelength agile, adjustable penetration depth
- Image buried layers -> overlay metrology
- X10-100 faster, x1000 lower cost/image vs Zeiss AIMS®
- Technology scalable to 6.7nm and 1nm





Materials characterization

- Monitor in-situ growth: reflection/photoemission
- Thin films, elastic properties, ellipsometry
- Magnetic materials, band bending, band structure



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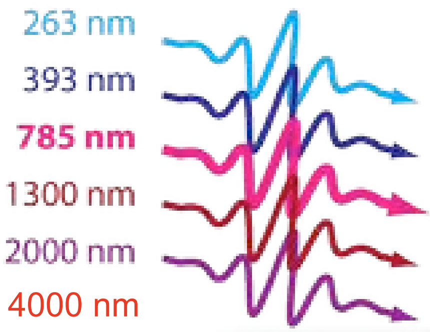
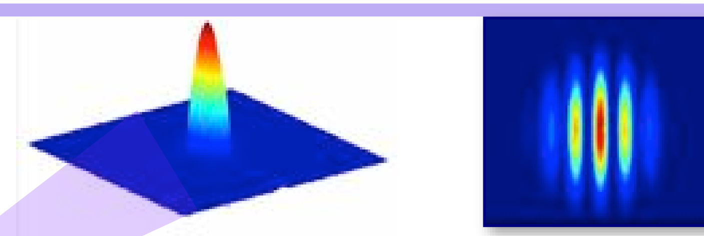
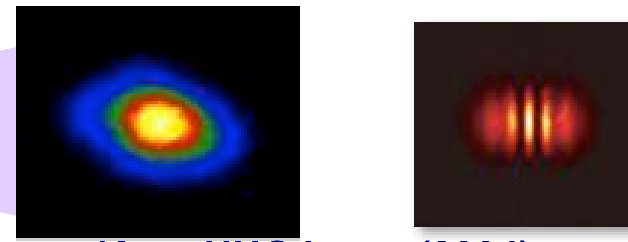
Current conversion efficiency from laser to HHG energy/power



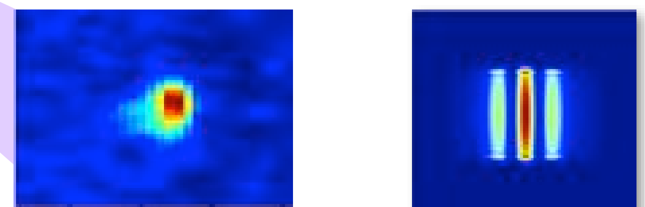
High pressure waveguide
Excellent coherent buildup and flux



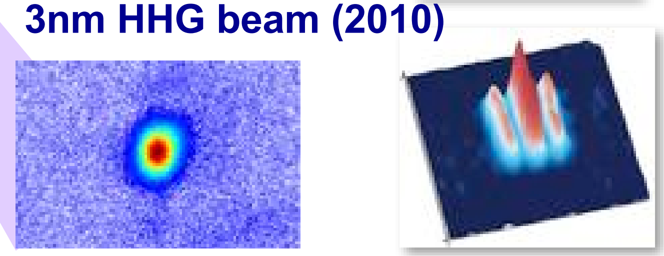
30nm HHG beam (2002)



13nm HHG beam (2004)



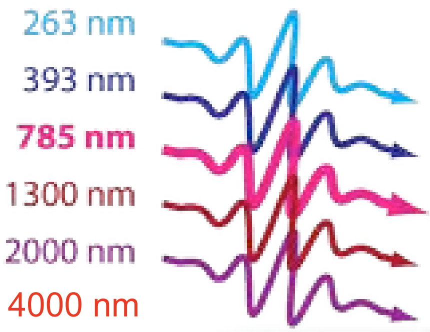
3nm HHG beam (2010)



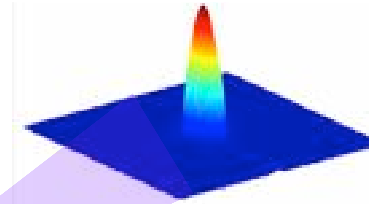
1nm HHG beam (2012)

Science ***280****, 1412 (1998)*
Science ***297****, 376 (2002)*
PNAS ***106****, 10516 (2009)*
Science ***336****, 1287 (2012)*
Science ***348****, 530 (2015)*
Science ***350****,1225 (2015)*

Current conversion efficiency from laser to HHG energy/power

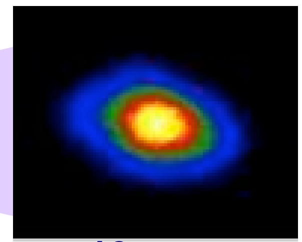


High pressure waveguide
Excellent coherent buildup and flux



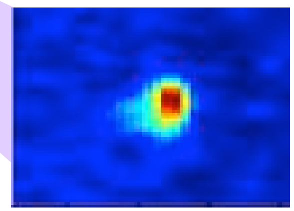
ε ~ 10^{-3} -10^{-5}
Synchrotron level

VUV and EUV



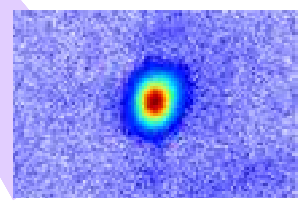
13nm

ε ~ 10^{-6}

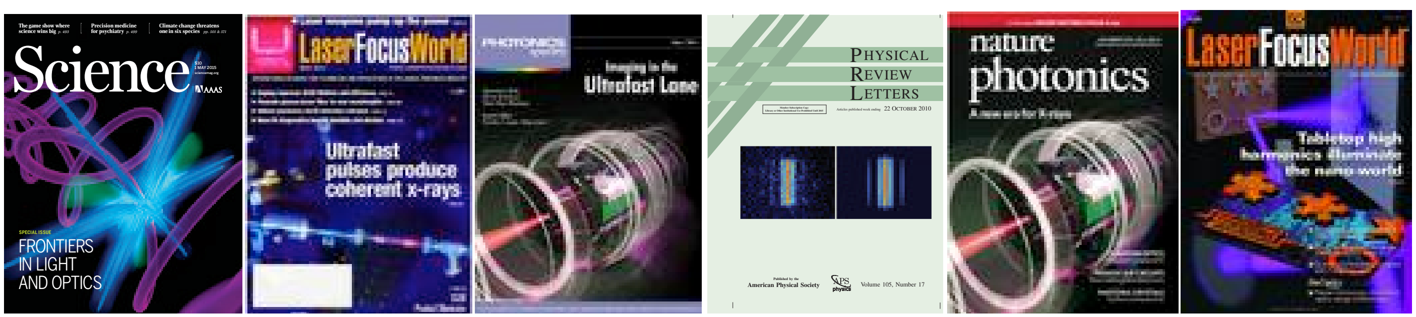


3nm Soft X-ray

ε ~ up to 10^{-7}
Needs easy MIR lasers with >>1W (mJ, kHz) power

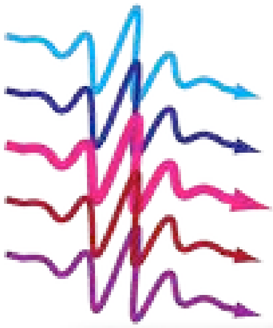


1nm Soft X-ray

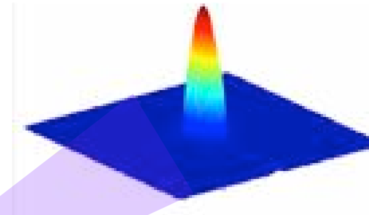


Science ***280****, 1412 (1998)*
Science ***297****, 376 (2002)*
PNAS ***106****, 10516 (2009)*
Science ***336****, 1287 (2012)*
Science ***348****, 530 (2015)*
Science ***350****,1225 (2015)*

Current conversion efficiency from laser to HHG energy/power

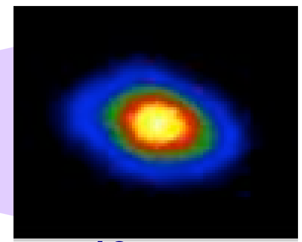


High pressure waveguide
Excellent coherent buildup and flux



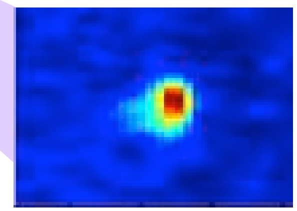
VUV and EUV

µW to mW
(few W drive laser)



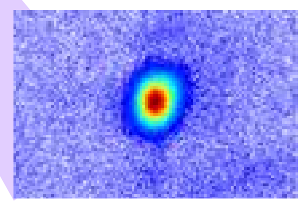
13nm

≈ µW
(few W drive laser)

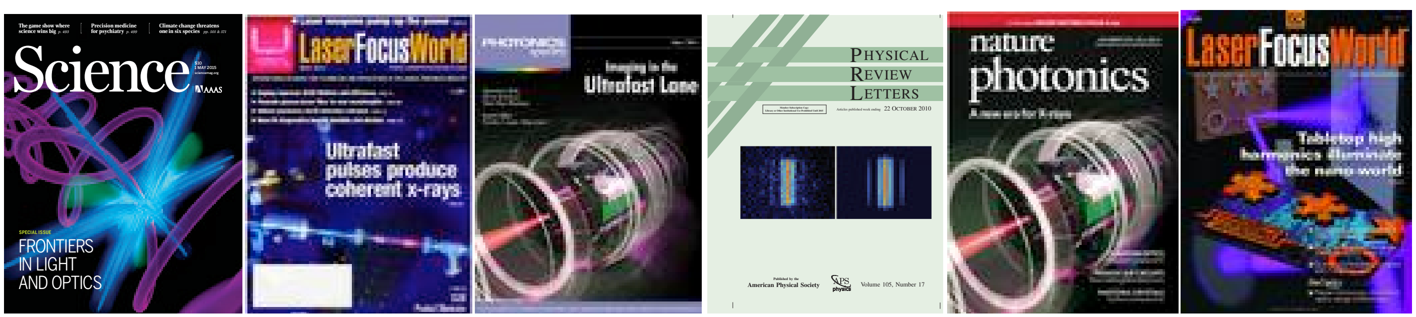


3nm Soft X-ray

≈ 10-100nW
(few W drive laser)



1nm Soft X-ray

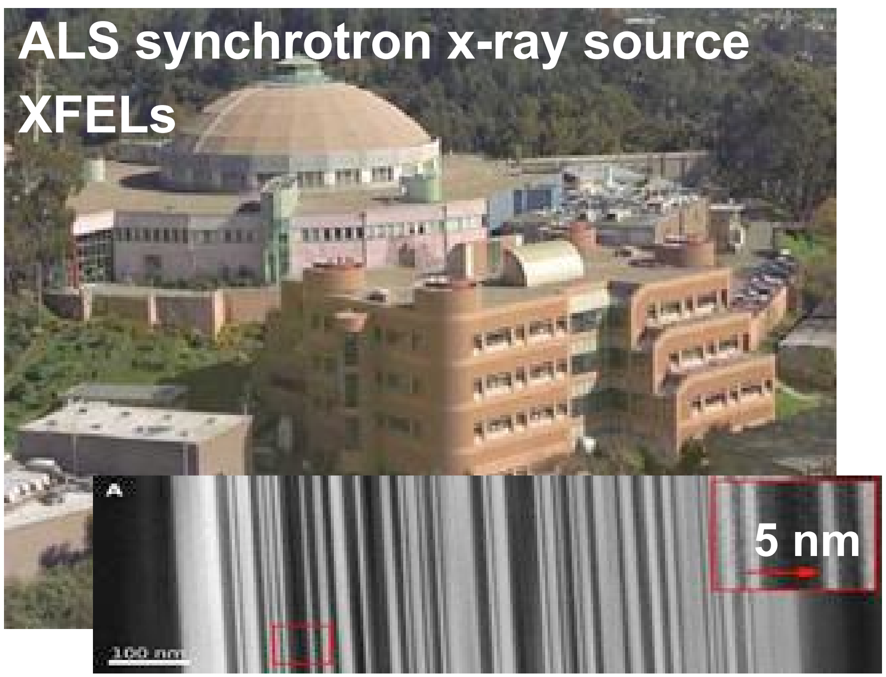


Science ***280***, *1412 (1998)*
Science ***297***, *376 (2002)*
PNAS ***106***, *10516 (2009)*
Science ***336***, *1287 (2012)*
Science ***348***, *530 (2015)*
Science ***350***, *1225 (2015)*

Revolution in coherent X-ray sources

Facility scale

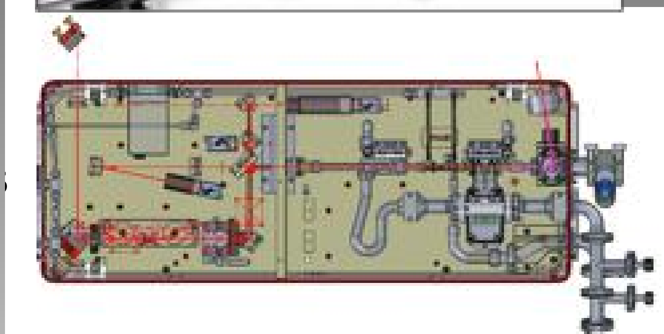
- Synchrotron and free electron lasers
- EUV to 12 keV (EUV to hard X-rays)
- Nano to femto time resolution
- 5nm spatial resolution CDI
- High flux
- Tunable
- Facility scale beamline access w/support

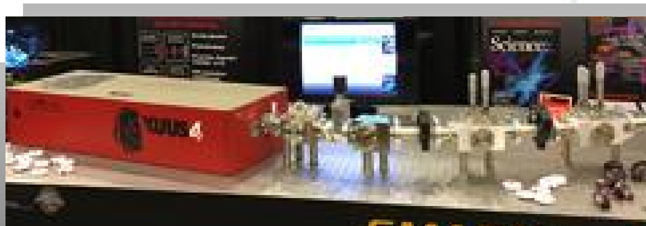


Tabletop

- High harmonic sources
- mid-IR to 1 keV (EUV to soft X-rays)
- Sub-femtosecond time resolution
- 12nm lateral/3Å axial spatial resolution
  Medium flux
- Hyperspectral
- Tabletop for easy student/industry access

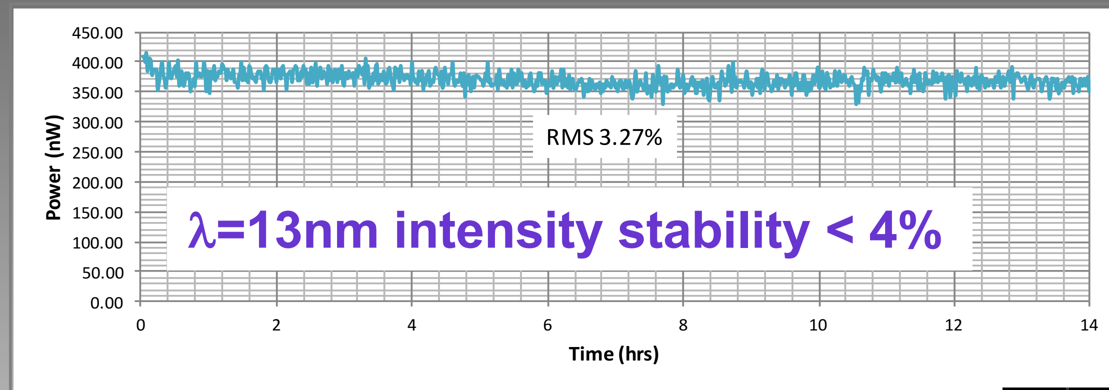
KMLabs XUUS™: tabletop-scale ultrafast X-ray laser with visible-laser stability





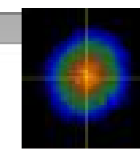
2009

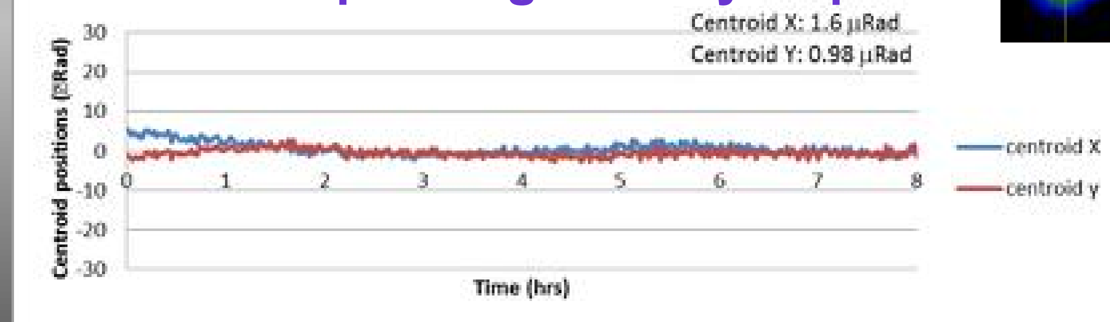
2016

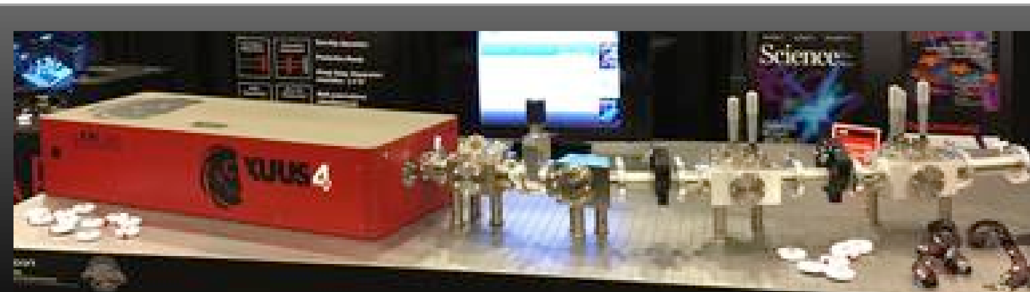


λ=13nm intensity stability < 4%

λ=13nm pointing stability ≈ 1μrad







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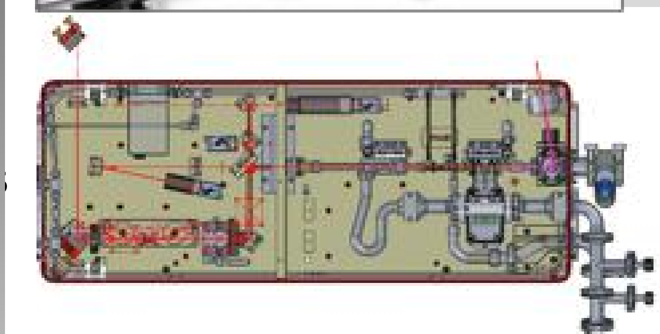
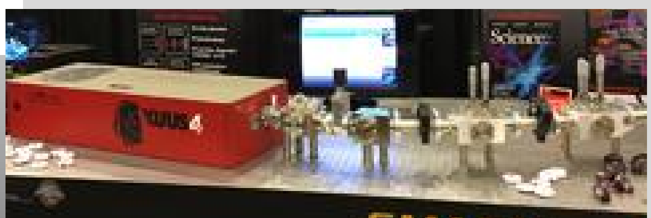
KMLabs XUUS™: *tabletop-scale ultrafast X-ray laser with visible-laser stability*

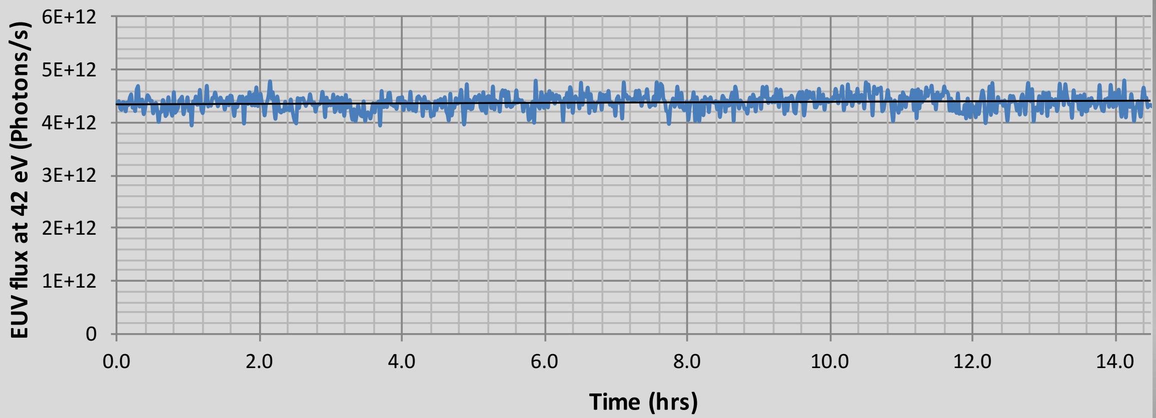




2009

2016

Coherent flux and stability similar to Synchrotron source!!



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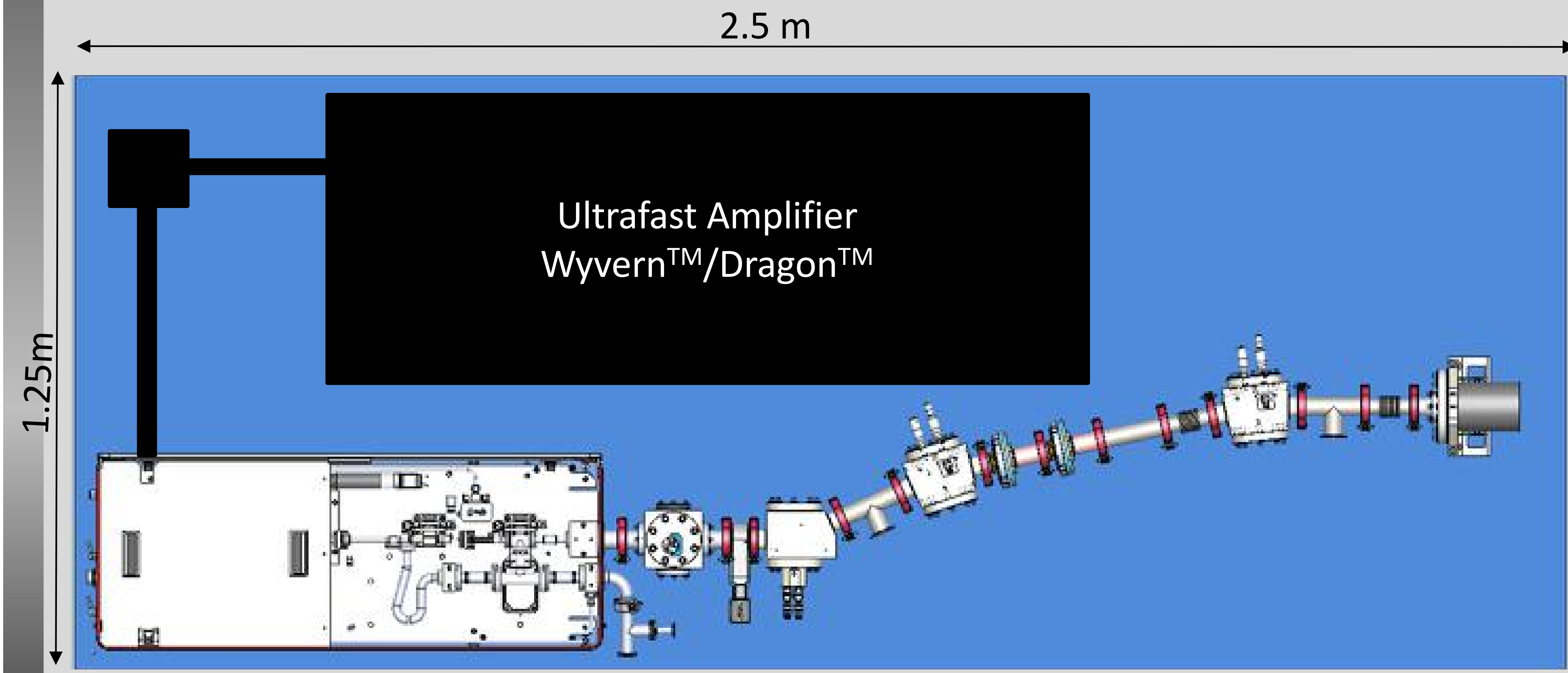
KMLabs XUUS™: *a truly integrated source*

- Truly Integrated HHG light source



- Automatic laser beam alignment
- A complete set of beamline modules to delivery the exact EUV beam parameters suited for your application
- Light source and optical components optimized for compatability, best throughput.

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KMLabs XUUS™: Product Specifications for Standard 2-10W lasers

Key Specifications:

XUUS Source Product Specifications					
HHG Wavelength	30 nm		18 nm	13 nm	6.7 nm
Photon Flux at Source	>5 x10^{12} ph/sec /1% BW		>10^{10} ph/sec /1% BW	>10^{10} ph/sec/1% BW	>10^{8} ph/sec
Driving Lasers	• 0.5mJ, <40fs • 10kHz, 5W • 800 nm	• 0.2mJ <40fs • 50kHz, 10W • 800 nm	• 2mJ, <40fs • 3kHz, 6W • 800 nm	• 3mJ, <40fs • 3kHz, 9W • 800nm	• 2mJ, <50fs • 1kHz, 2W • 1400 nm
	Wyvern 1000-10	Wyvern 500	Wyvern 1000-10	Wyvern 1000-10	Wyvern HE + OPA
Pulse Duration	HHG produces attosecond pulses or pulse trains depending on the implementation. The FWHM envelope in the simplest implementation is < 15fs using 40fs Wyvern, and <10fs using 21fs DRAGON				
Linewidth	Linewidth variable from 100meV to quasi-continuum (depends on laser parameters)				
Pointing Stability	<5µRad RMS				
Power Stability	<4% RMS (100ms integration time)				
Mode Quality	Near TEM_{00}				
Divergence	Depends on waveguide diameter, 0.5 - 4 mrad typical				

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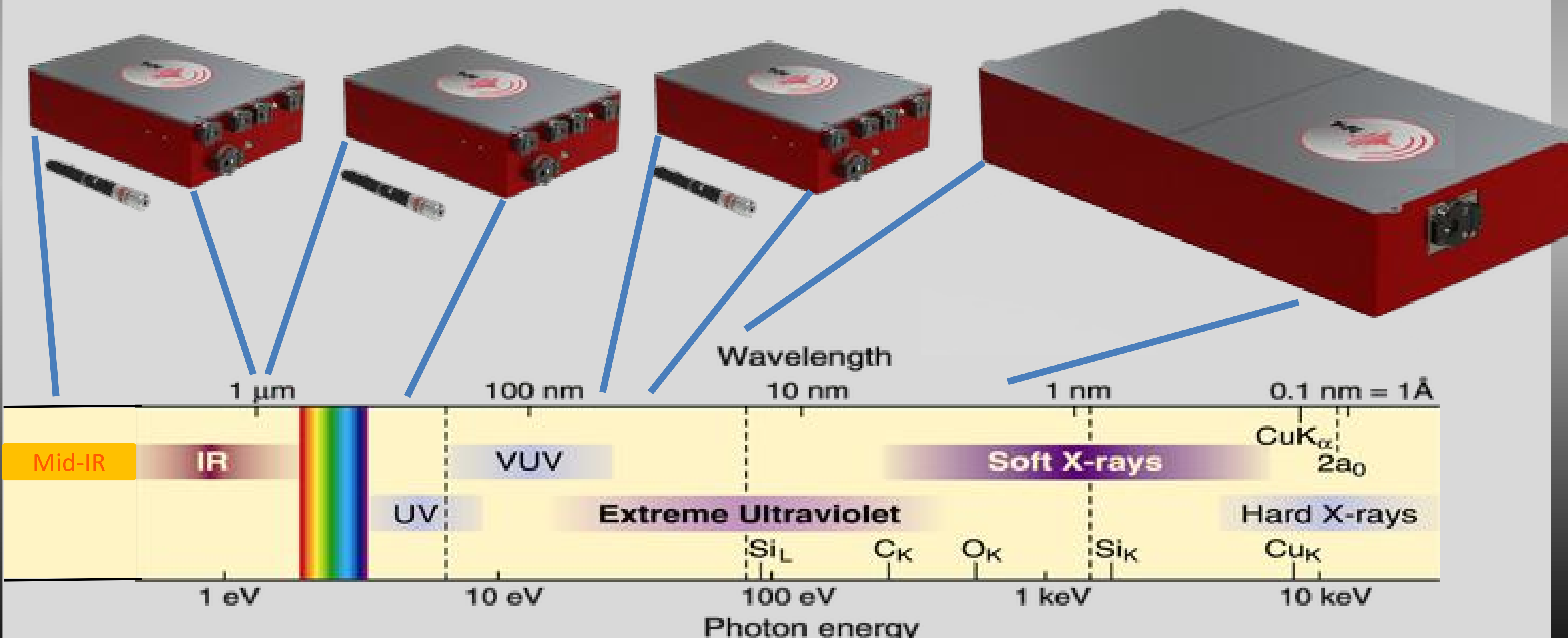
KMLABS inc. LEADING IN ULTRAFAST

Record ultrafast <100fs fiber lasers:

small footprint, increased stability, MIR to VUV

Y-Fi™

Y-Fi™ OPA **Y-Fi™ SHG** **Y-Fi™ VUV** **Y-Fi™ HP Ultra/OPCPA series**



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KMLabs Y-Fi™: *Product Specifications*

Parameter	Y-Fi™	Y-Fi™ HP	Y-Fi™ HP Ultra
Pulse Width	<150 fs (<120 fs typical)	<170 fs	<190 fs
Compressor Dispersion Pre-compensation	±20,000 fs^2	±10,000 fs^2	Inquire
Center Wavelength	1035 ± 5 nm	1035 ± 5 nm	1035 ± 5 nm
Pulse Energy	> 0.45 μJ @ 10 MHz	> 3 μJ @ 1 MHz	> 40 μJ @ 1 MHz
Peak Power	> 3 MW, calculated via FROG	> 10 MW, calculated via FROG	> 80 MW, calculated via FROG
Beam Quality	$M^2 < 1.2$	$M^2 < 1.2$	$M^2 < 1.2$
Average Power	> 4.5 W @ 10 MHz	> 20 W @ 10 MHz	> 50 W @ 10 MHz
Repetition Rate	0.5 - 15, 60 MHz	0.5 - 15, 60 MHz	0.5 - 15, 60 MHz
Auto-Correlation Pedestal Content	< 12%	< 15%	< 20%
Background content	< 1.0%	< 1.0%	< 2.0%
Pre-Pulse Contrast	< 0.5%	< 0.5%	< 1%
Post-Pulse Contrast	< 0.5%	< 0.5%	< 1%
Power Stability*	<1% RMS over 12 hours after 30 min warm-up	<1% RMS over 12 hours after 30 min warm-up	<1% RMS over 12 hours after 30 min warm-up
Pointing Stability*	< 10 μRad RMS after 30 min warmup	< 10 μRad RMS after 30 min warmup	Inquire
Operational Temp. Range	16 – 26 °C	16 – 26 °C	16 – 26 °C
Physical Configuration	12"x16"x2.4" (optical head)	12"x16"x2.4" (optical head)	24"x48"x8" (optical head)
Computer Interface	Laptop provided, w/GUI	Laptop provided, w/GUI	Laptop provided, w/GUI
SHG Power	Inquire	> 8 W @ 10 MHz	Inquire
SHG Pulse Duration	Inquire	< 150 fs	Inquire

* Ambient ± 0.5 C

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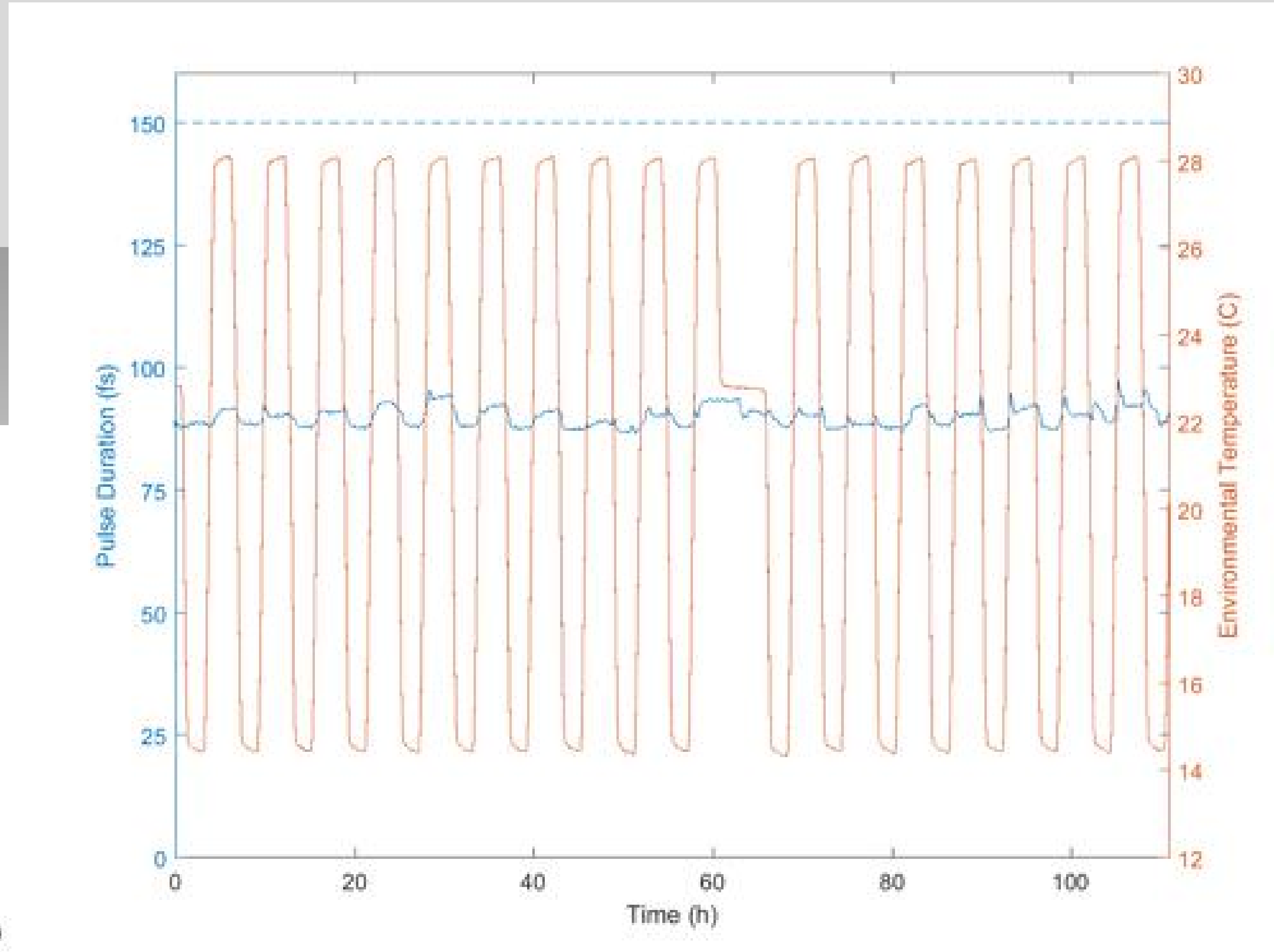
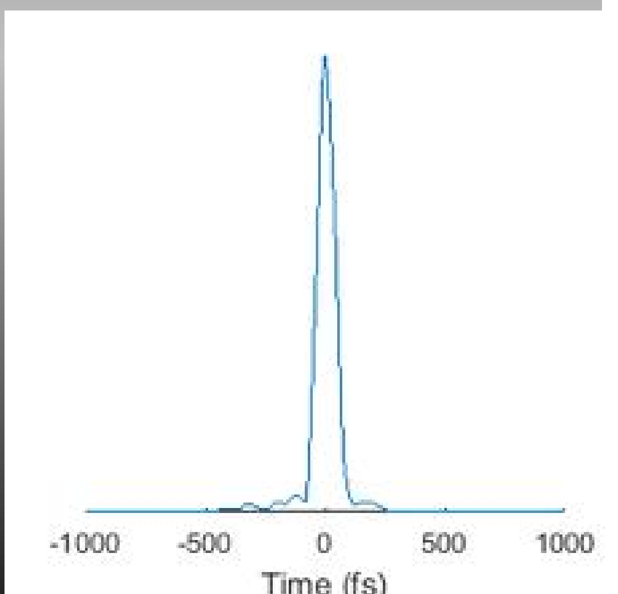
KMLabs Y-Fi™: Temperature Cycling

- Pulse duration over >100 hours of temperature cycling ± 8°C
- Average: 90 fs
- RMS deviation: 2.2 fs
- Passive cooling
- Active cooling better





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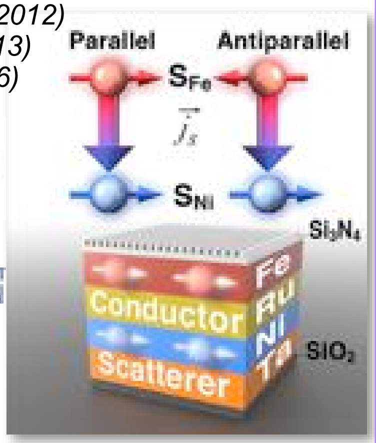
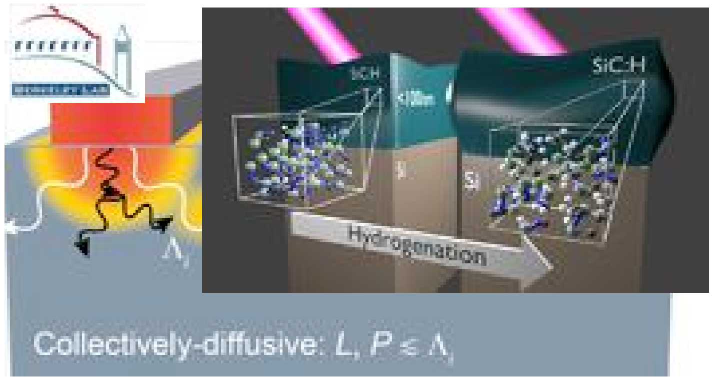
HHG has moved beyond demos or POC:
uncovering new materials/nano science

Spin dynamics in magnetic materials

PNAS **109**, 4792 (2012)
Nat. Comm. **3**, 1037 (2012)
PRL **110**, 197201 (2013)
PRB **94**, 220408 (2016)

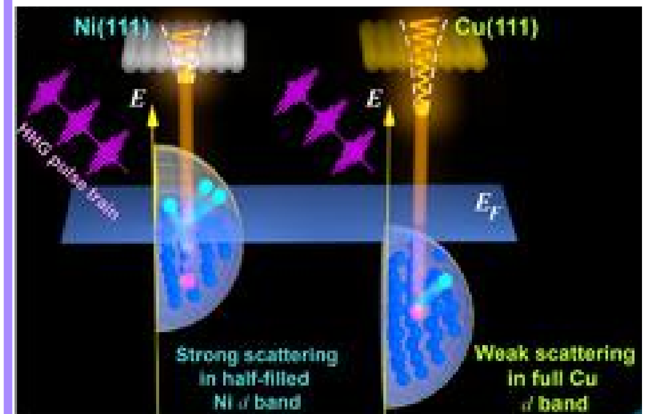


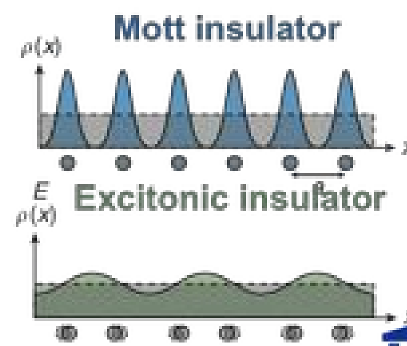
Nanoscale mechanical properties, energy transport



Nature Mat. **9**, 26 (2010); *PRB* **85**,195431 (2012)
PNAS **112**, 4846 (2015); *Nano Lett.* **16**, 4773 (2016);
Nano Letters **17**, 2178 (2017)

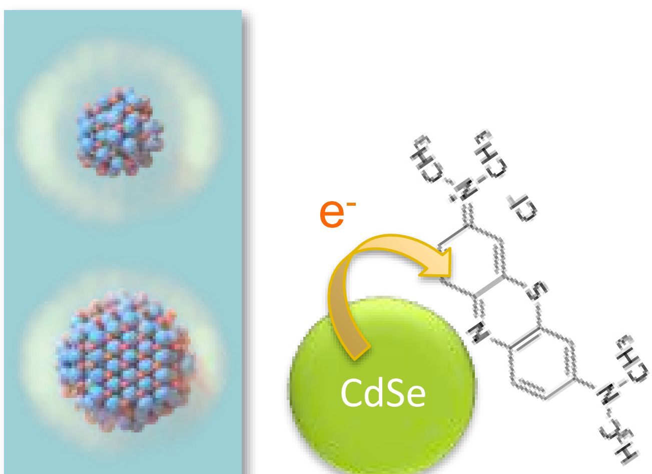
Tr-ARPES: Time & Angle-Resolved Photoemission





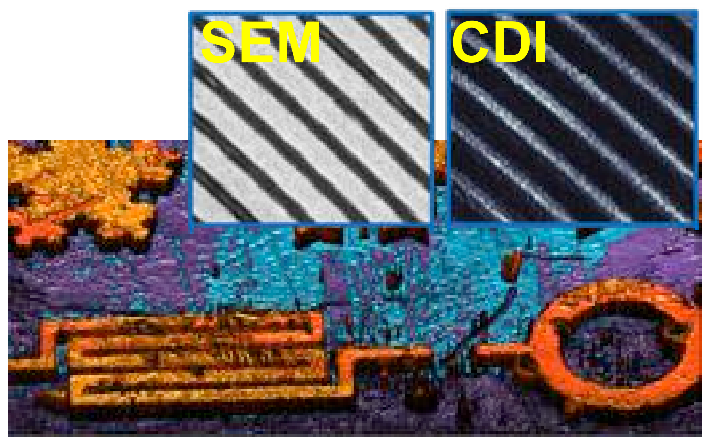
PNAS, in press (2017)
Science **353**, 62 (2016)
Science **353**, 28 (2016)
Science Advances **3**, e1602094 (2017)
Nature **471**, 490 (2011)
Nat. Comm **3**, 1069 (2012)
PRL **112** , 207001 (2014)
PRB **92**, 041407 (2015)
Nature Comm. **7**, 12902 (2016)

Charge transport in nano-materials



Nano Lett. **13**, 2924 (2013)
JACS **137**, 3759 (2015)

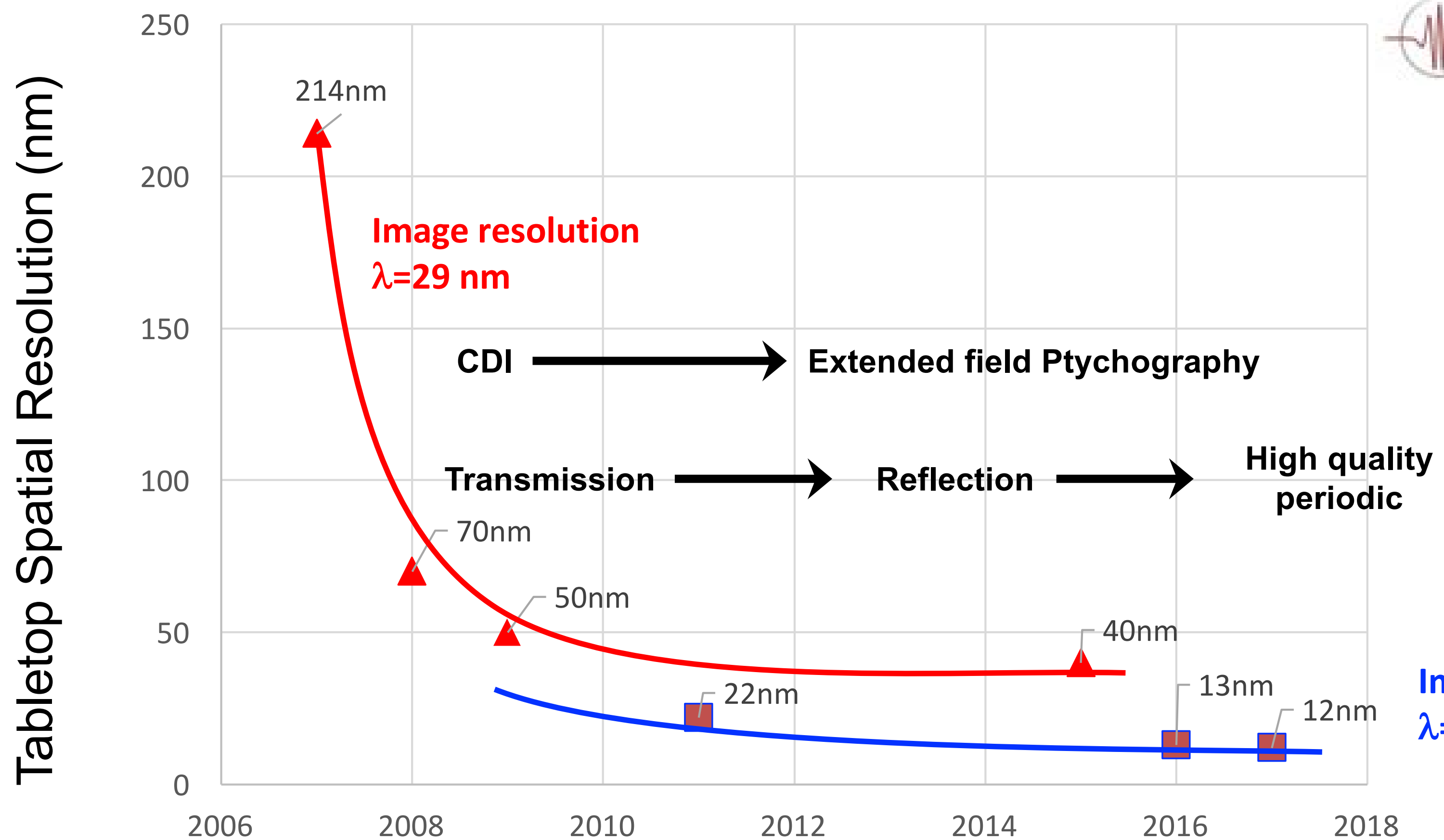
1st sub-wavelength EUV/X-ray imaging



Science **348**, 530 (2015); *Ultramicroscopy* **158**, 98 (2015)
Nano Lett. **16**, 5444 (2016); *IQT* **8**, 18 (2016);
Nature Photonics **11**, 259 (2017)

EUV coherent imaging: *a disruptive technology*

- Record spatial resolution of 0.9λ: 12.6nm using 13.5nm XUUS™ HHG beams
- Full field imaging of near-periodic structures, with record speed
- Can scale to shorter wavelength, higher resolution, deeper penetration



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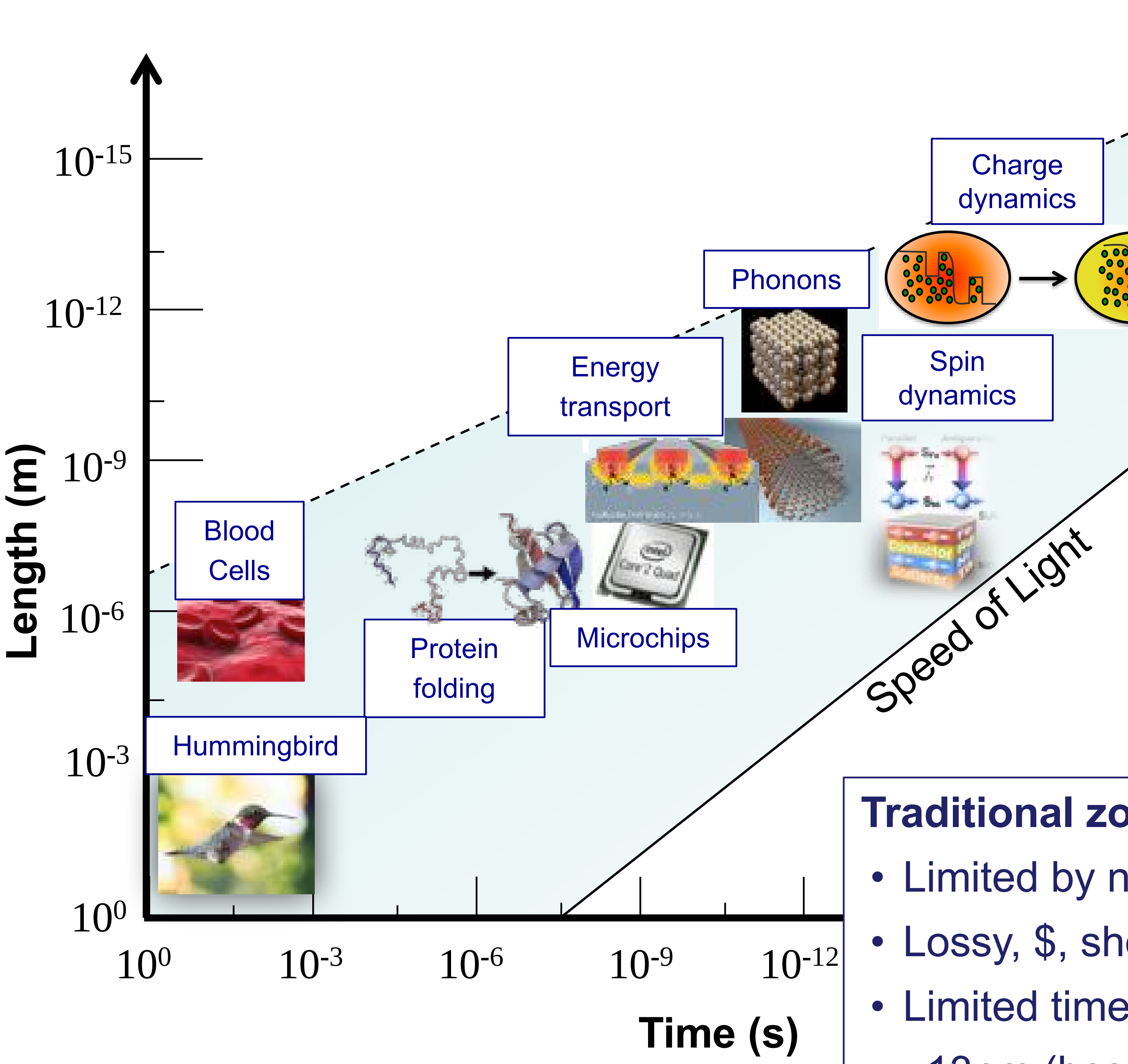
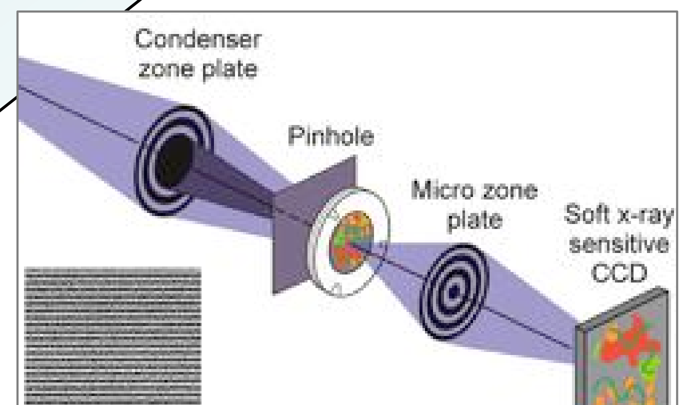
Traditional X-ray microscopy





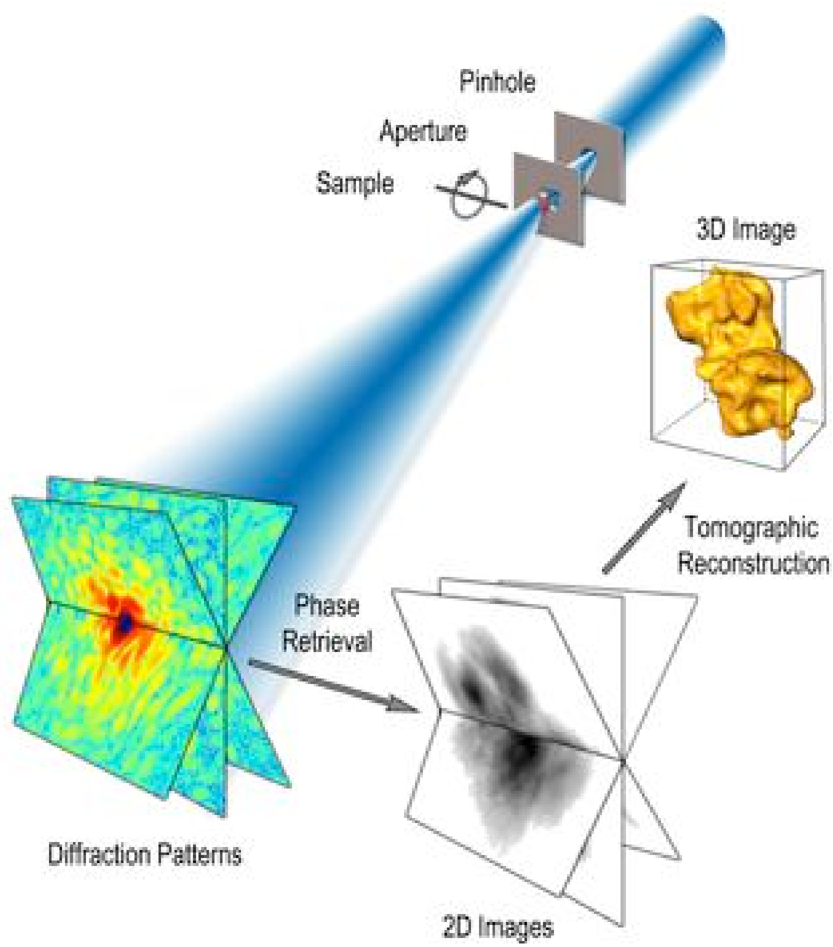
Nature ***435,*** *1210 (2005)*

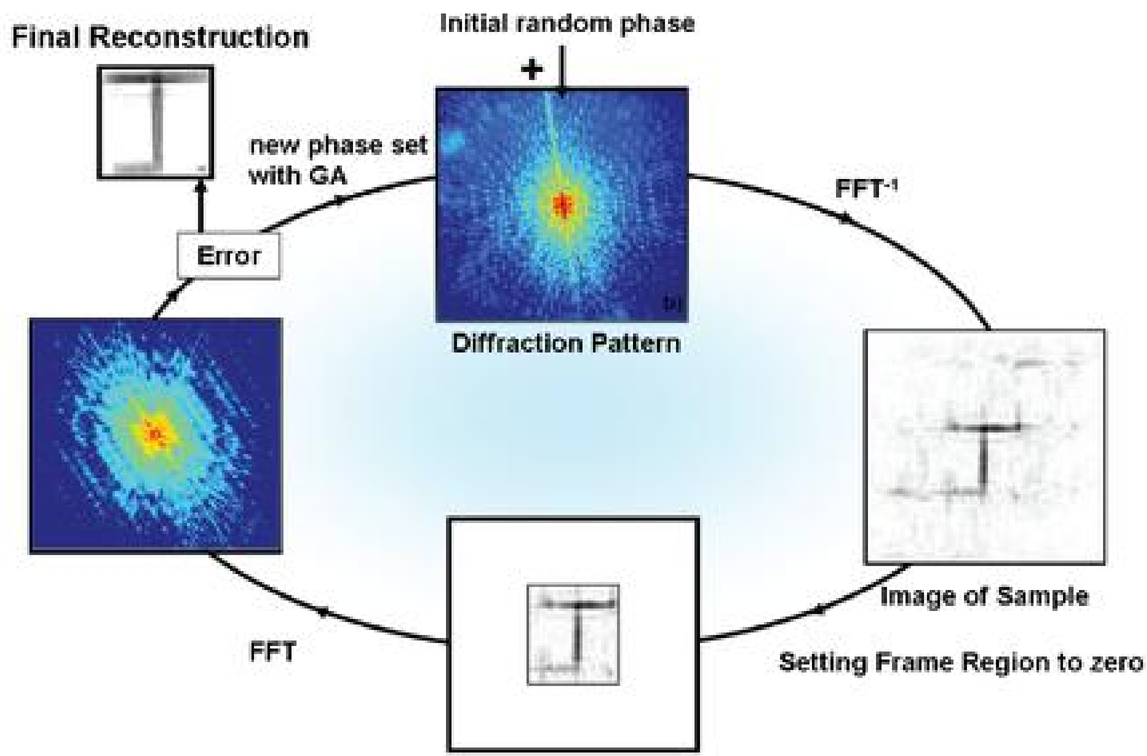
Traditional zone-plate microscopes

- Limited by nanofabrication
- Lossy, $, short depth of focus lens
- Limited time resolution (> ps)
- ≈13nm (best), 25nm (typical) resolution

Revolution in Coherent X-Ray Imaging (CDI)

- **Diffraction-limited imaging ≈ λ/2NA**
- Image thick samples in 3D
- Inherent contrast for X-rays
- Phase and amplitude image contrast
- Robust to vibrations
- MOST photon-efficient form of imaging!



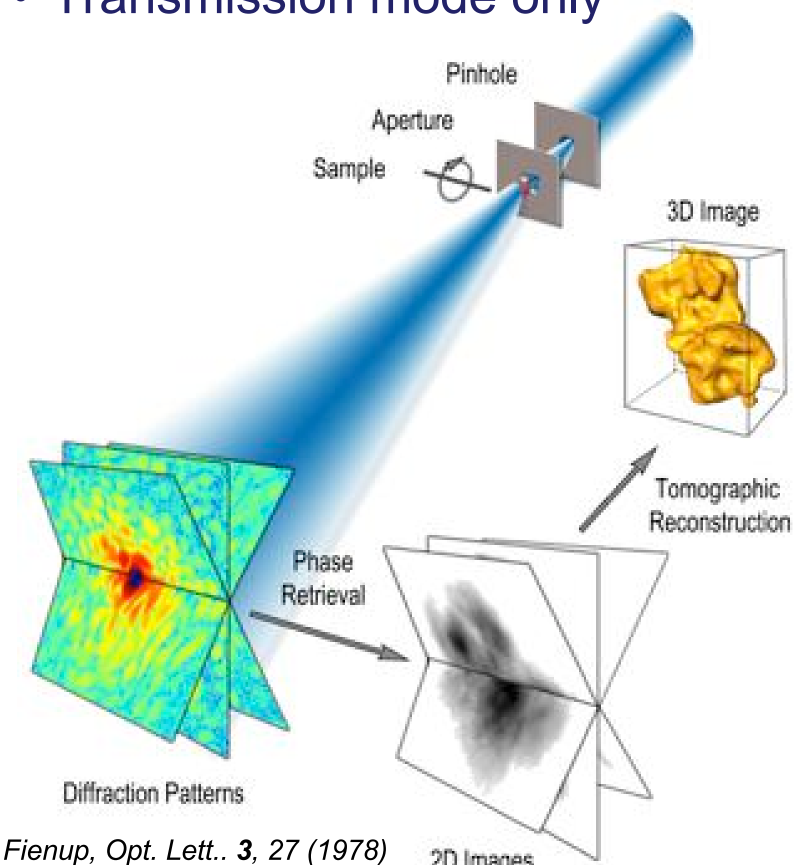


Sayre, Acta Cryst ***5****, 843 (1952)*
Miao et al., Nature ***400****, 342 (1999)*

Advances in coherent diffractive imaging (CDI)

Initial approaches to CDI (2011)

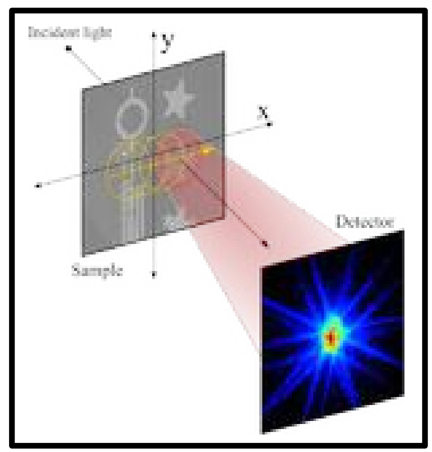
- Required isolated sample or beam
- Simple algorithms
- Average multiple reconstructions
- Transmission mode only

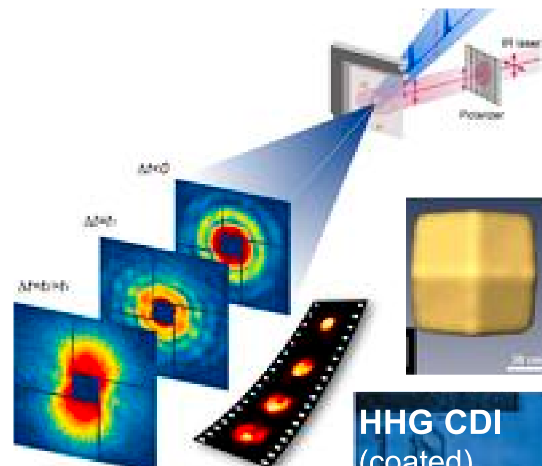


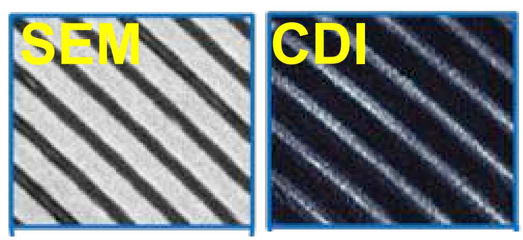
*Fienup, Opt. Lett.. **3**, 27 (1978)*
*Miao et al., Nature, **400**, 342 (1999)*
*Rodenburg et al., PRL **98**, 034801 (2007)*
*Thibault et al., Science **321**, 379 (2008)*
*Maiden et al., Ultramicroscopy **109**, 1256 (2009)*

Advanced CDI (2016)

- Ptychographic CDI from overlapping areas
- Robust reflection and transmission imaging
- Quantitative imaging, buried interfaces
- Hyperspectral, multibeam
- Periodic and non-periodic samples with MEP

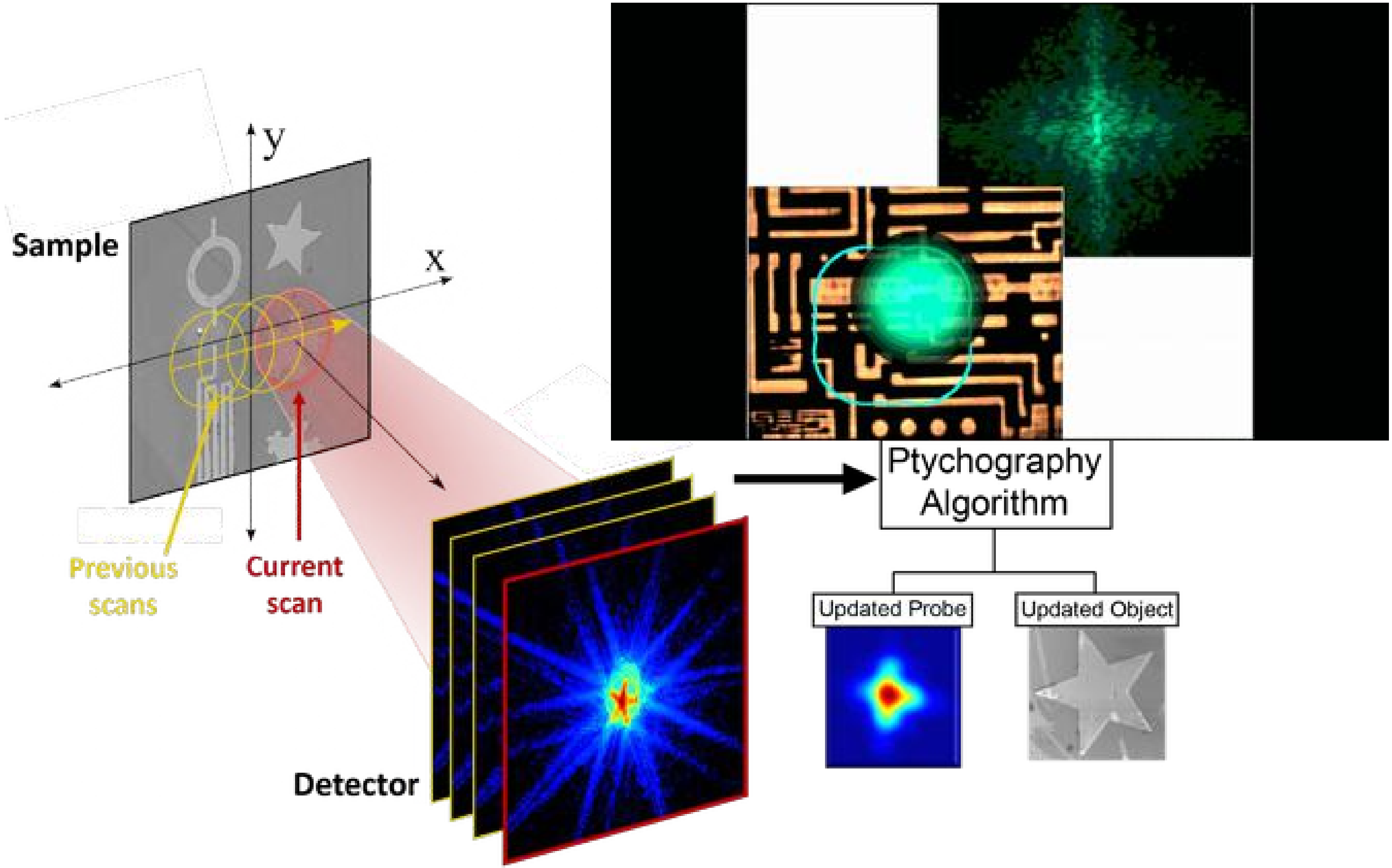






*Miao et al., Science **348**, 530 (2015)*
*Zhang et al., Ultramicroscopy **158**, 98 (2015)*
*Shanblatt et al., Nano Letters **16**, 5444 (2016)*
*Kapteyn et al, IQT **8**, 18 (2016)*
*Gardner et al., Nature Photonics **11**, 259 (2017)*

Ptychography: CDI with multiple diffraction patterns to enhance redundancy



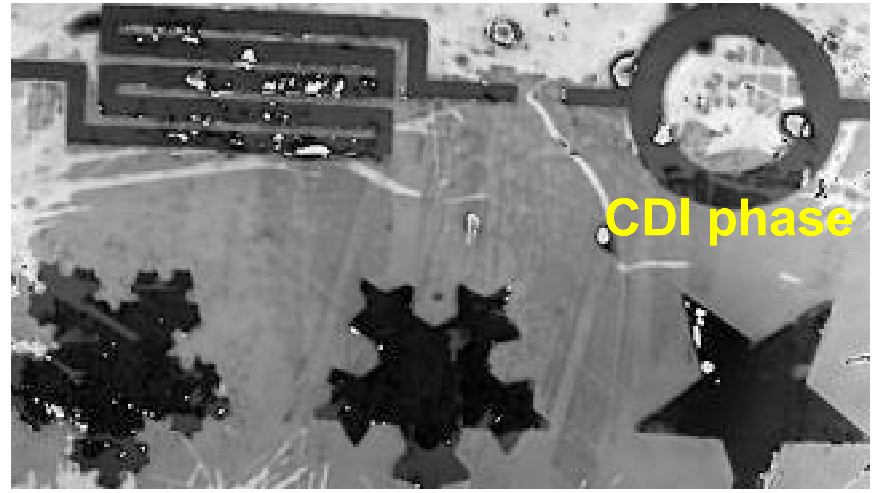
Theoretical resolution depends on numerical aperture (≤1):

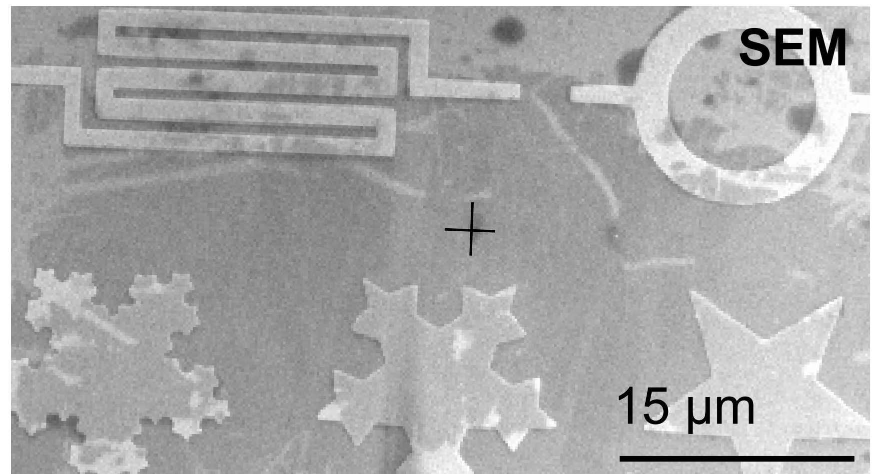
$$\Delta r = \frac{\lambda}{2\,NA}$$

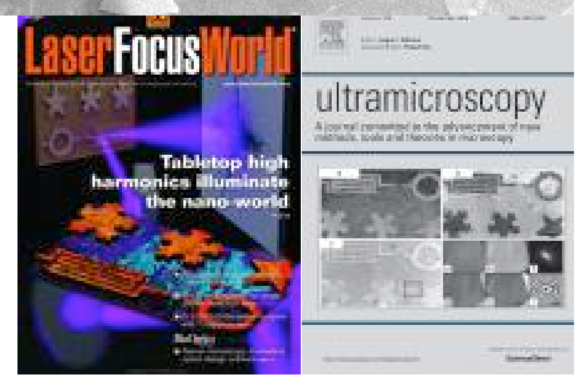
*Rodenburg et al., PRL **98**, 034801 (2007)*
*Thibault et al., Science **321**, 379 (2008)*
*Maiden et al., Ultramicroscopy **109**, 1256 (2009)*

High contrast tabletop CDI (λ = 30nm)

- Better contrast images than JILA SEM due to phase contrast imaging
- 3D imaging: spatial resolution 1.3λ horizontal (<40nm), <5Å vertical
- 22nm resolution in transmission (1.6λ)
- Very rapid 1 minute data acquisition time
- Less damage then AFM or SEM
- Long working distance of 10 cm

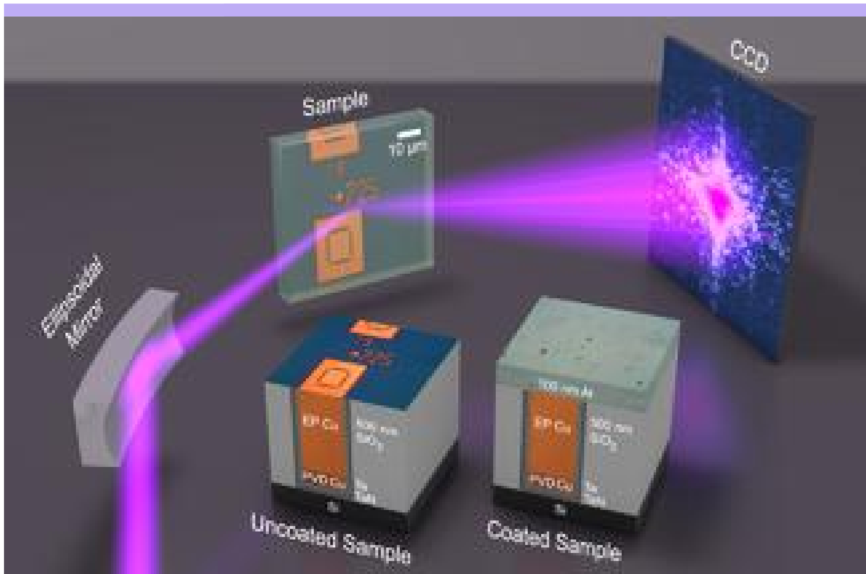




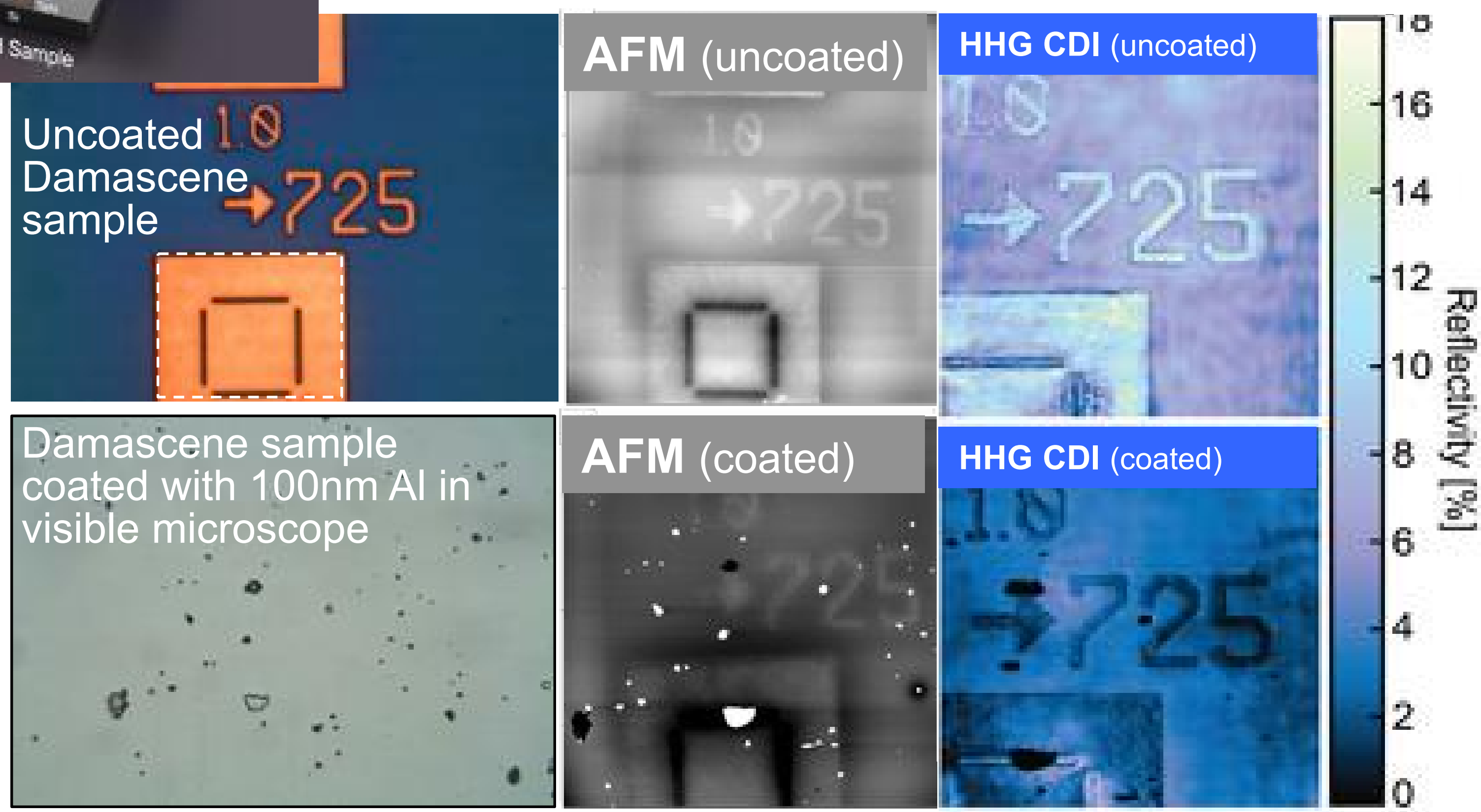


Optica ***1***, *39 (2014)*
Science ***348***, *530 (2015)*
Laser Focus World (2015)
Ultramicroscopy ***158***, *98 (2015)*
Nano Letters ***16***, *5444 (2016)*
IQT ***8***, *18 (2016)*

Seeing through buried layers and interfaces

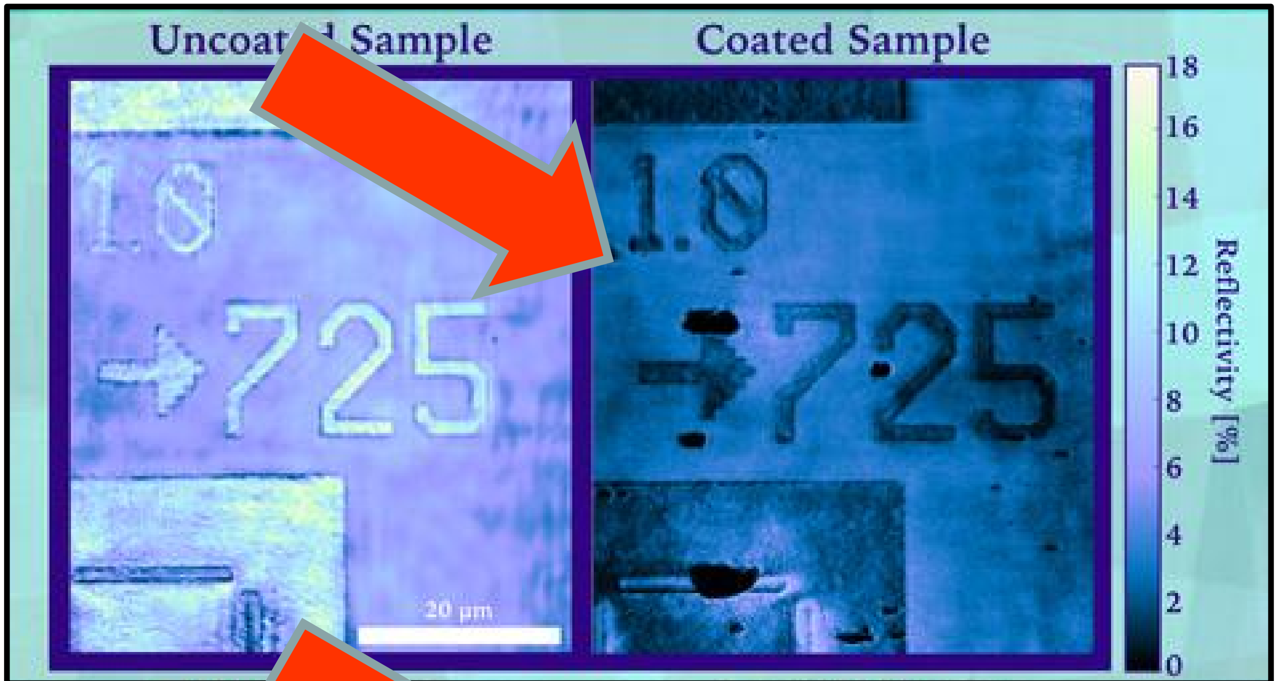


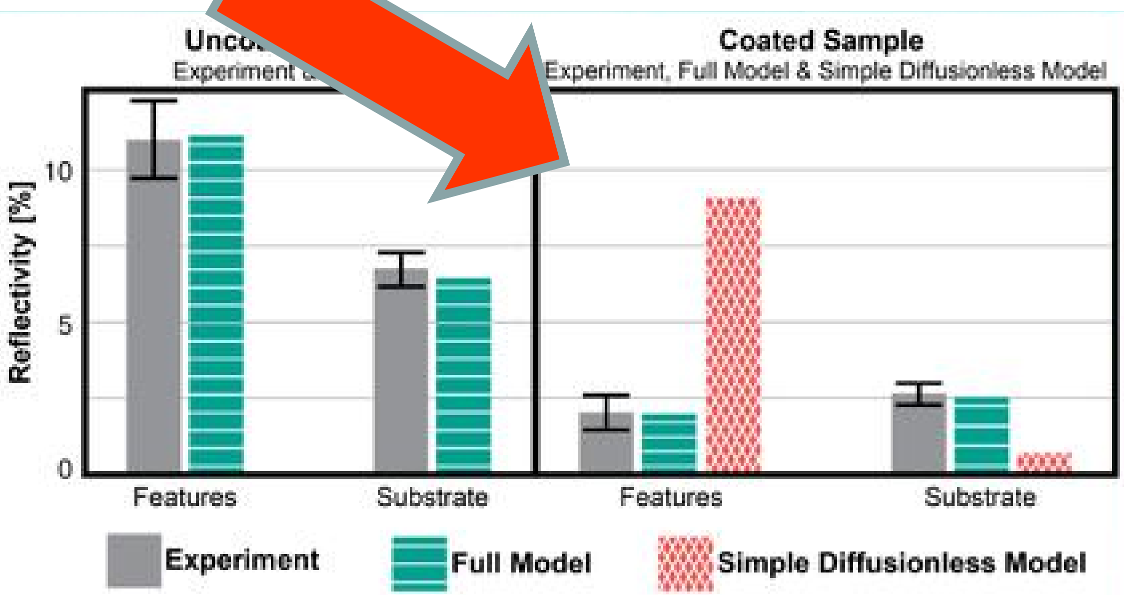
- **CDI amplitude** image enables imaging of elemental composition **through** 100nm of Al
- Quantitative non-destructive imaging of elemental & interfacial properties harnessing EUV reflectivity
- Identified interdiffusion of Al into Cu, and formation of thin Al oxide layer on SiO_2

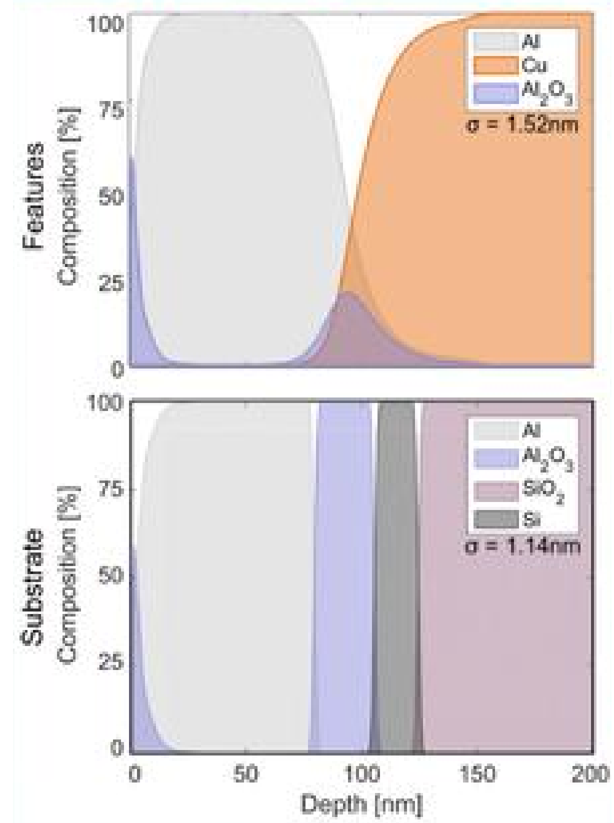


*Postdeadline paper, Frontiers in Optics (2015); Nano Letters **16**, 5444 (2016)*

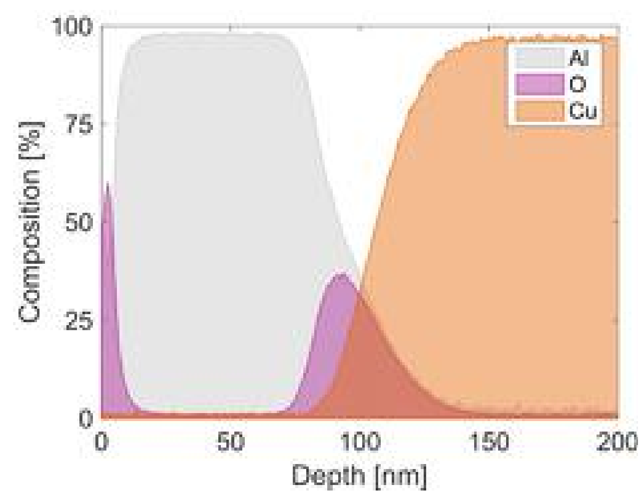
Nondestructive imaging of diffusion at buried interfaces





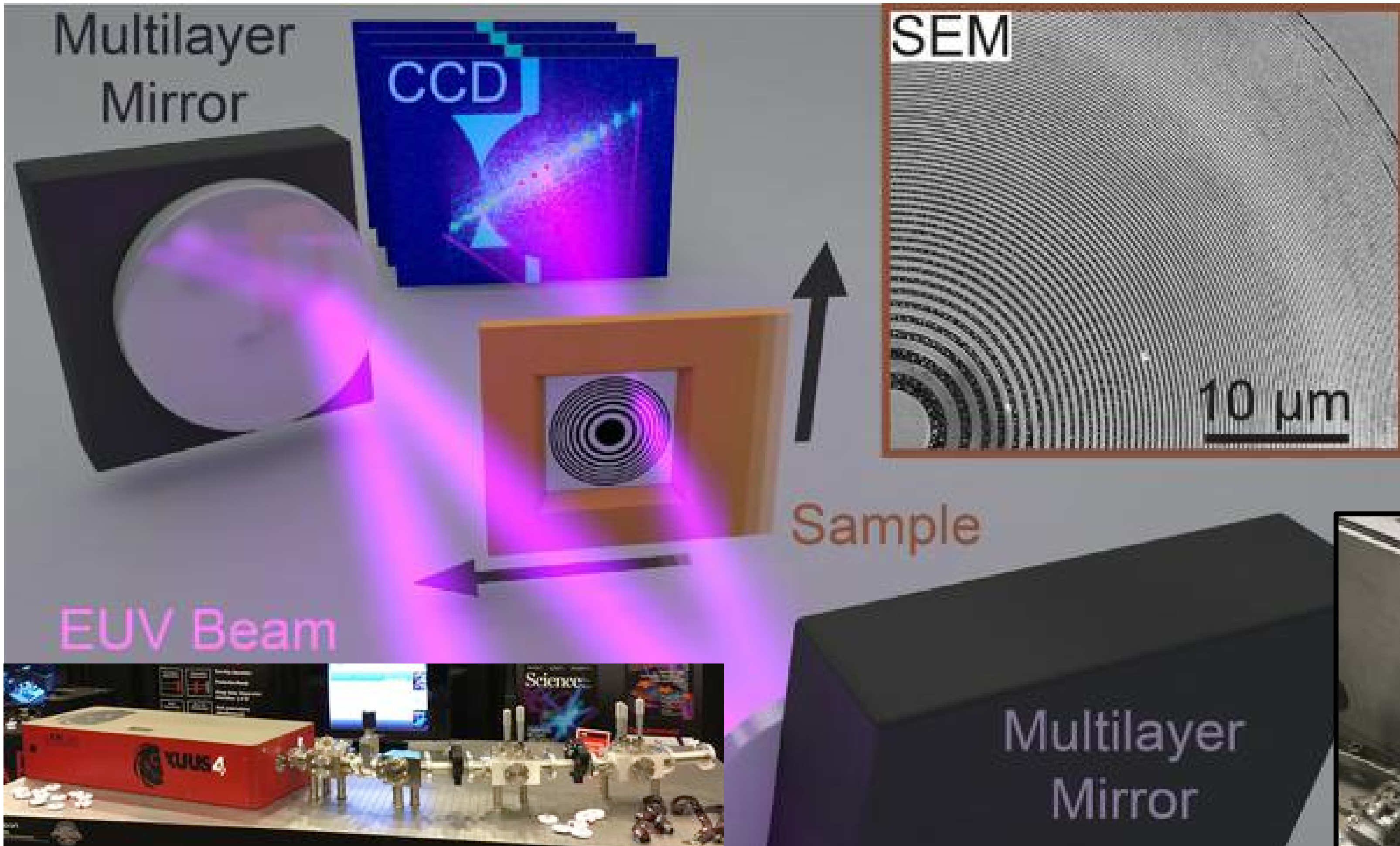


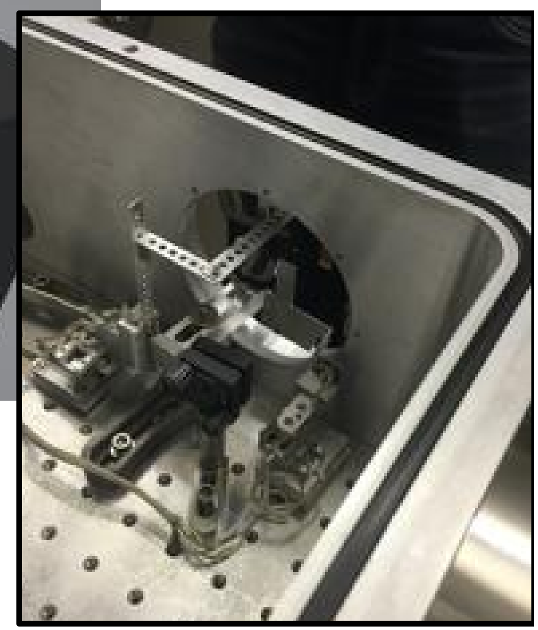
Theoretical Profiles



Auger Sputter Depth Profile

Record full field 13.5nm imaging using XUUS™

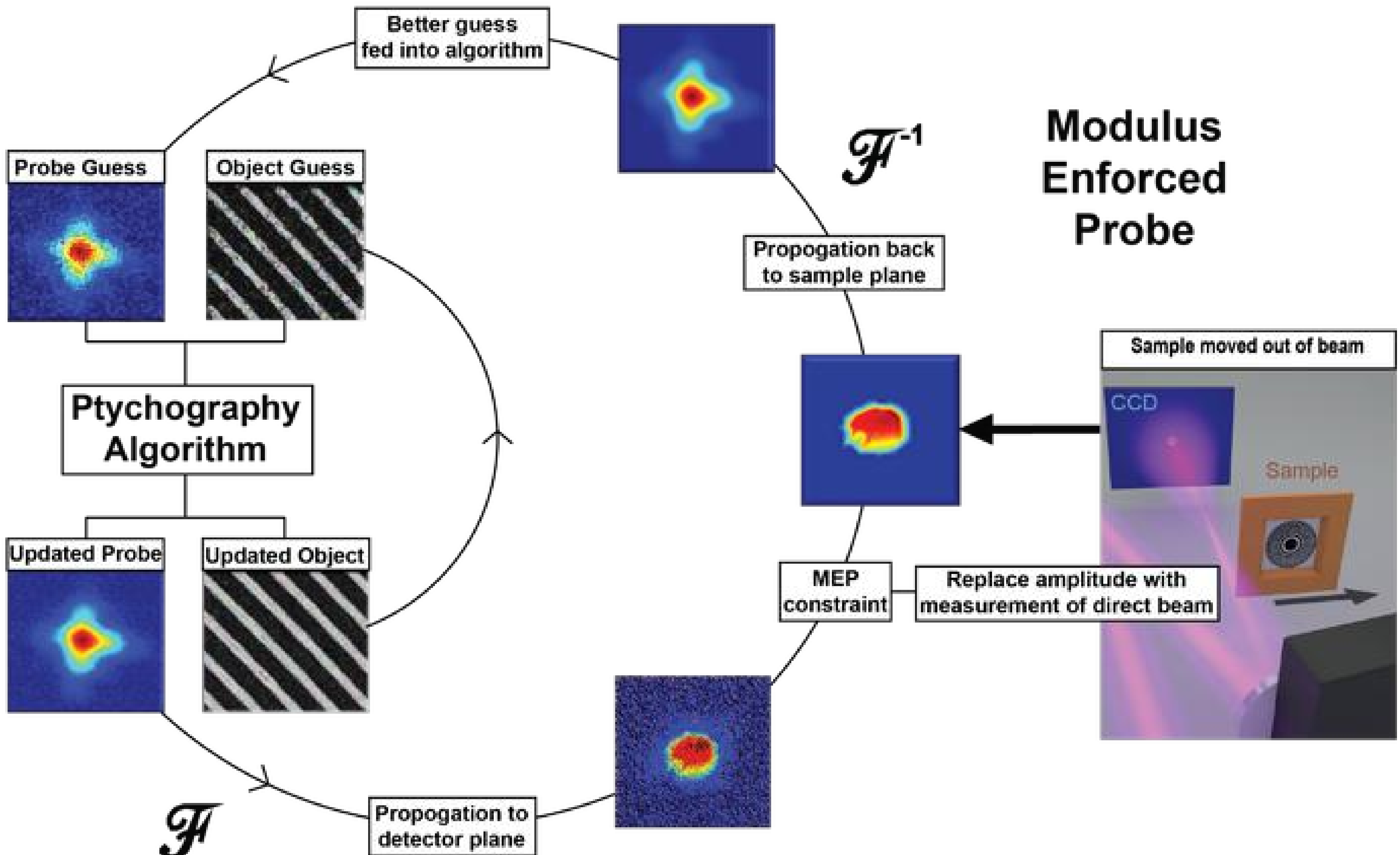




- Transmission mode 13.5 nm CDI microscope
- Stability of KMLabs XUUS™ was critical to demo
- Used a zone plate as a periodic sample
- NA of 0.54 only limited by size and distance to camera

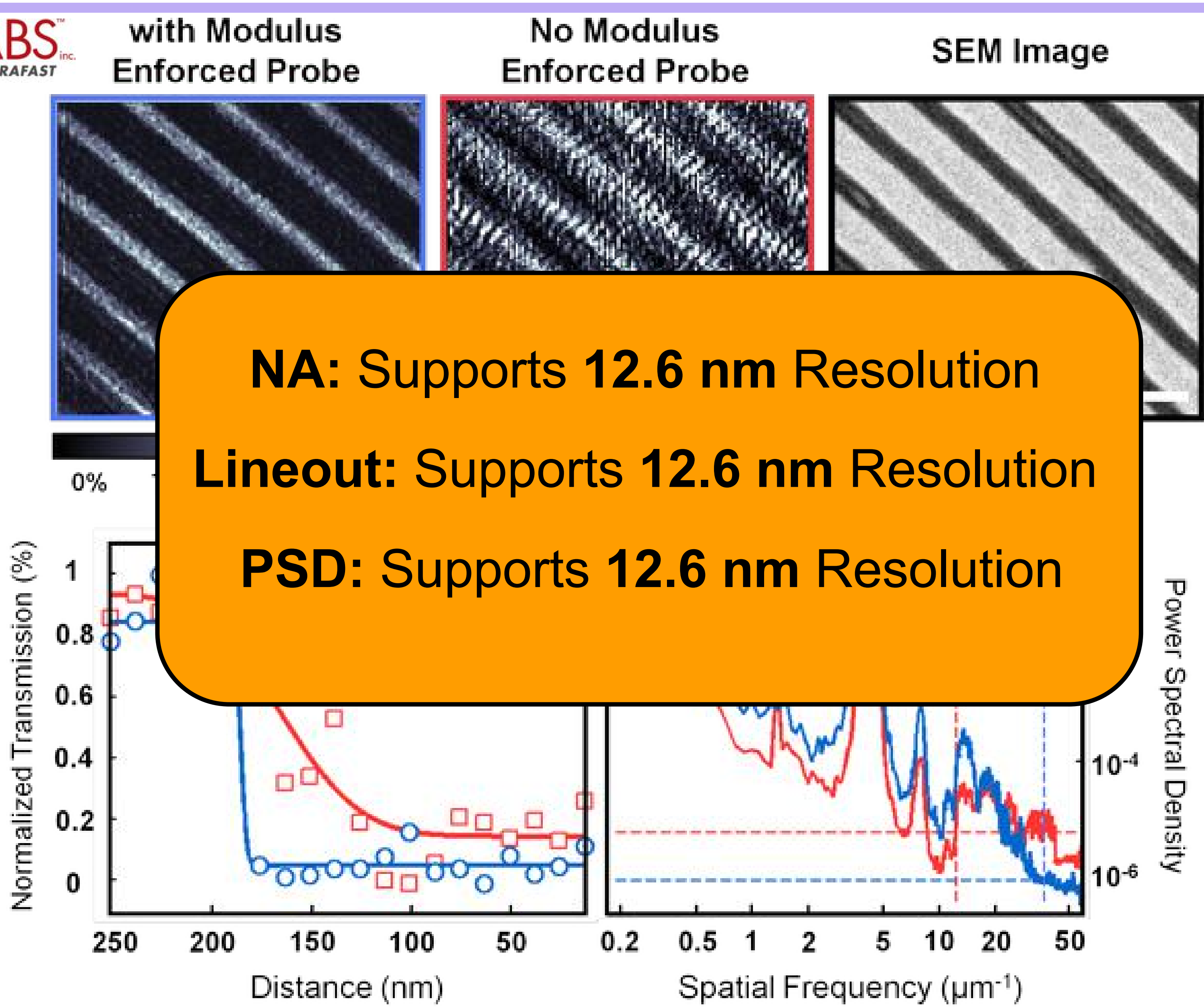
Modulus Enforced Probe

Measure HHG beam intensity to tightly constraint the guess of the illumination and avoid cross-talk between the sample and beam for periodic samples



Gardner et al., *Nature Photonics* ***11***, 259 (2017)

Quantifying the resolution



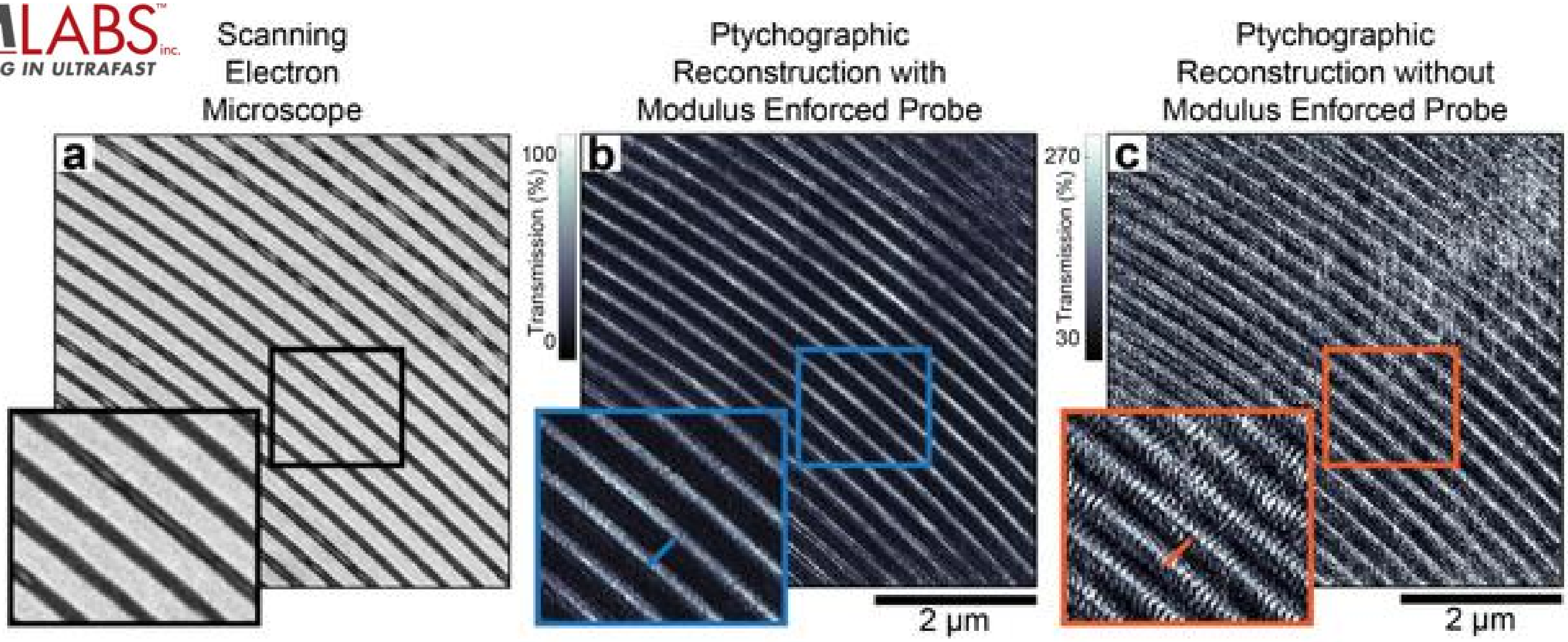
NA: Supports **12.6 nm** Resolution

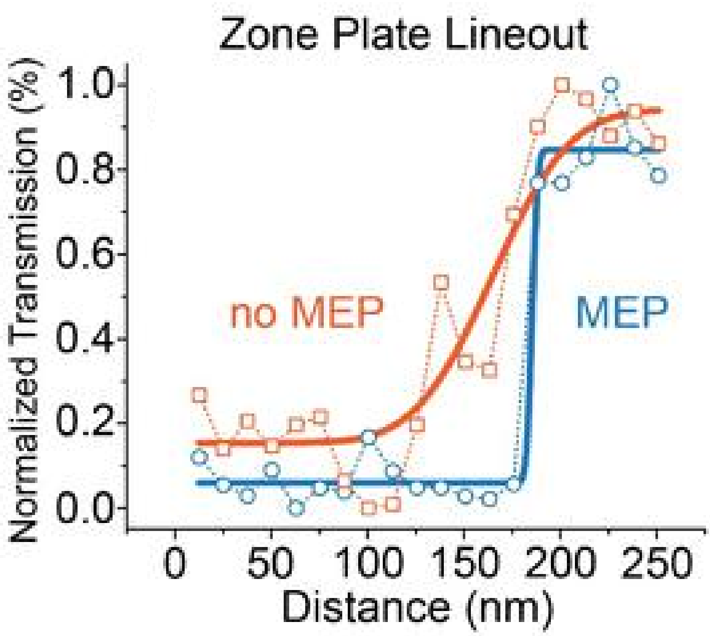
Lineout: Supports **12.6 nm** Resolution

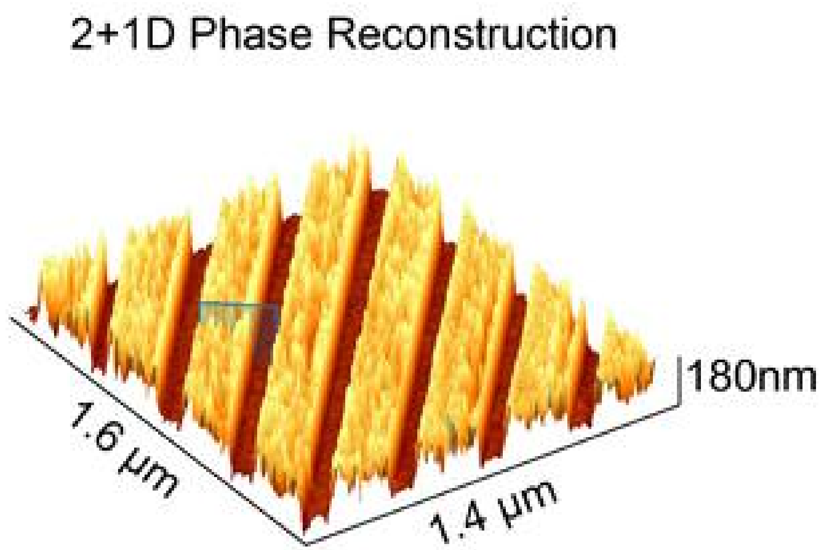
PSD: Supports **12.6 nm** Resolution

Gardner et al., Nature Photonics ***11****, 259 (2017)*

Record 1st sub-λ EUV imaging: 12.6nm resolution @ 13.5nm





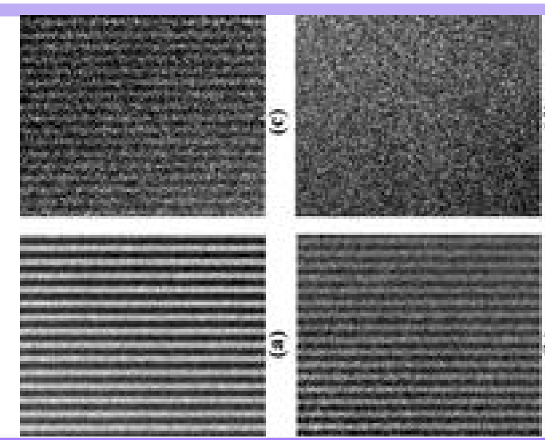


Gardner et al., Nature Photonics ***11****, 259 (2017)*

Record 1st sub-λ EUV imaging: 12.6nm resolution @ 13.5nm

Record zone plate imaging: synchrotron source (2009)

- Zone plate imaging at λ=13nm: spatial resolution ≈ 50nm
- Zone plate imaging at λ=2nm: spatial resolution ≈ 12nm
- Chao et al. Optics Express **17**, 17669 (2009)

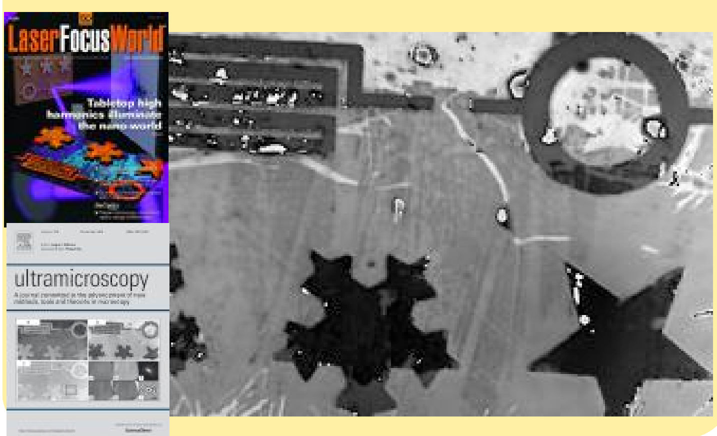


Record EUV imaging for any light source by 2016

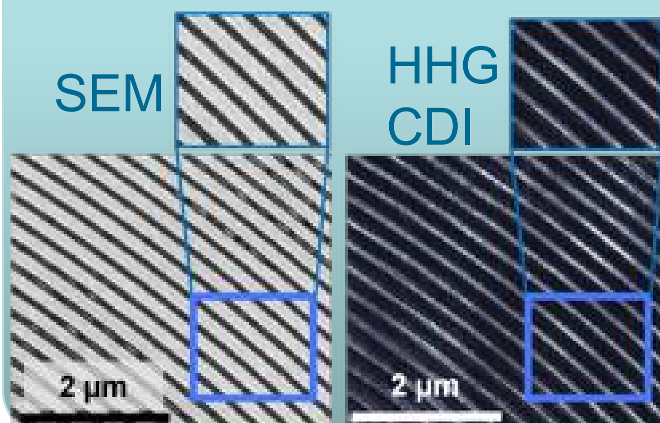
- Most powerful 13nm image: 1st sub-λ resolution (0.9λ, 12.6nm)
- Periodic or non-periodic samples
- High contrast, full field, images of REAL industry-relevant samples
- Quantitative imaging of buried interfaces
- Not yet reached limits in resolution or speed

*Miao et al., Science **348**, 530 (2015)*
*Zhang et al., Ultramicroscopy **158**, 98 (2015)*
*Shanblatt et al., Nano Letters **16**, 5444 (2016)*
*Kapteyn et al, IQT **8**, 18 (2016)*
*Gardner et al., Nature Photonics **11**, 259 (2017)*

Reflection mode HHG CDI



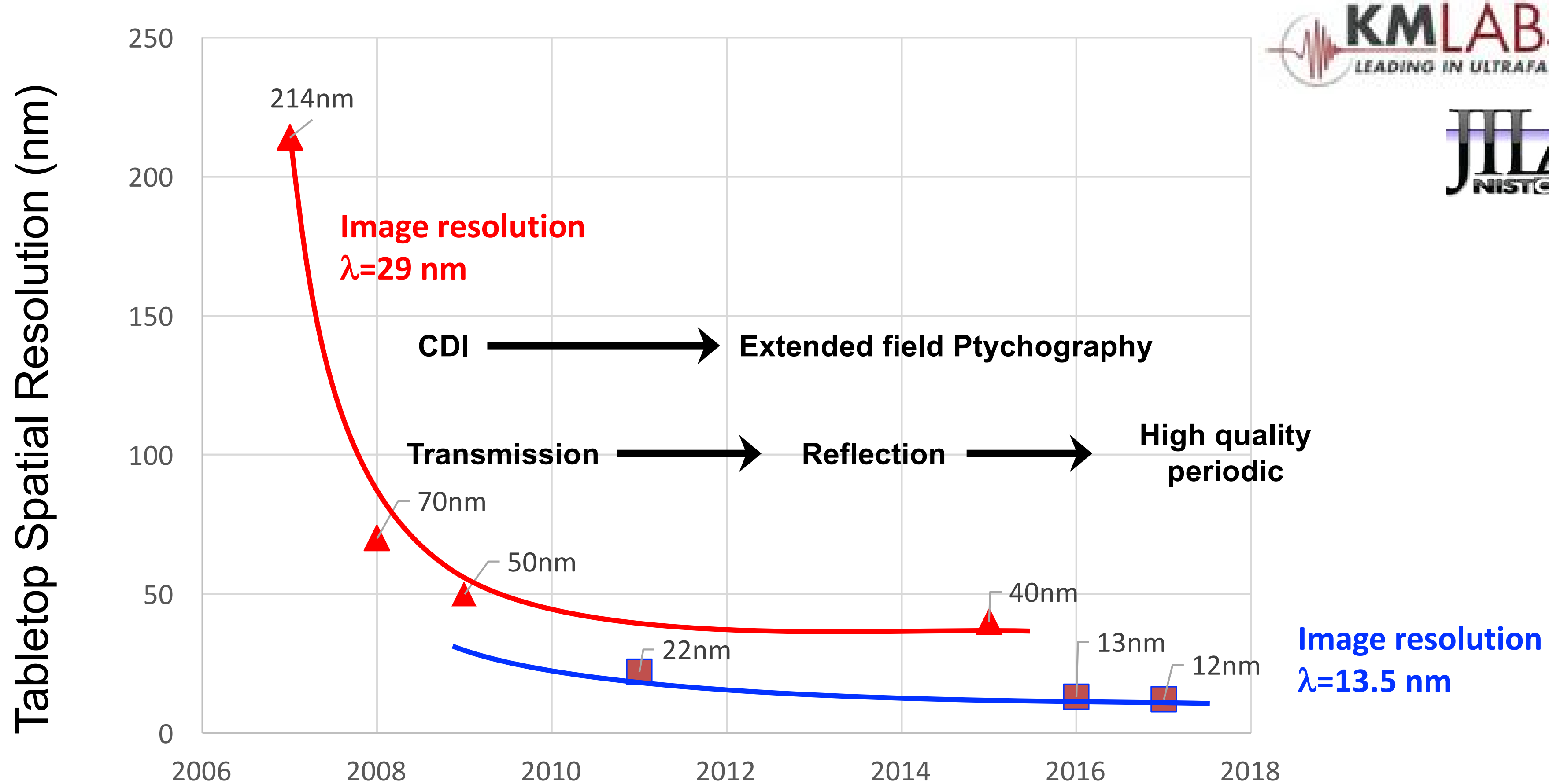
Record CDI at 13nm



Buried layer imaging

EUV coherent imaging:
a disruptive technology

- Record spatial resolution of 0.9λ: 12.6nm using 13.5nm XUUS™ HHG beams
- Full field imaging of near-periodic structures, with record speed
- Can scale to shorter wavelength, higher resolution, deeper penetration



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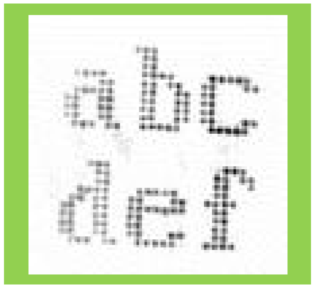
Advances in image quality using HHG CDI

1999: First X-ray CDI

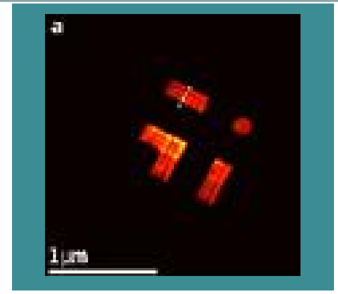


Nature **400**, 6747 (1999)

2007: First HHG CDI

PRL **99**, 9 (2007)

2011: 22 nm resolution

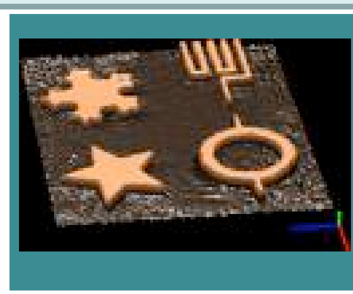


Opt. Ex. **19**, 22470 (2011)

2013: Semi-transparent

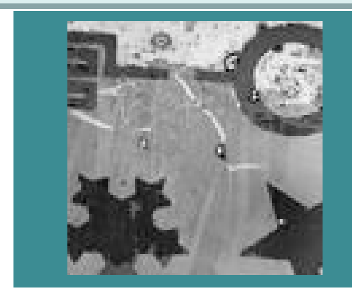
Opt. Ex. **21**, 19 (2013)

2014: First reflection



Optica **1**, 1 (2014)

2015: High NA reflection



Ultramicroscopy **158**, 98 (2015)

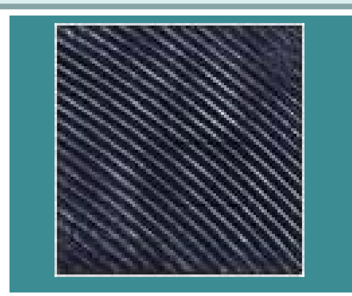
2016: Hyperspectral

Opt. Ex. **24**, 16 (2016)

2016: Quant. buried layer

Nano Lett. **16**, 5444 (2016)

2017: 1st sub-λ, periodic

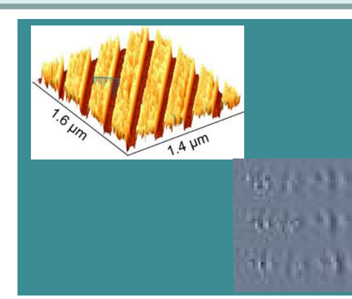


Nat. Photon. **11**, 22 (2017)

2017: Dynamic imaging

Postdeadline paper, CLEO (2017)

2017: 3D



In prep.

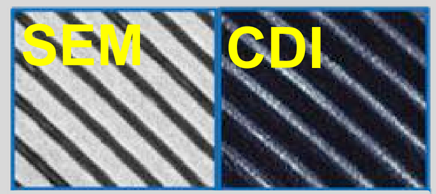
Applications relevant to EUVL

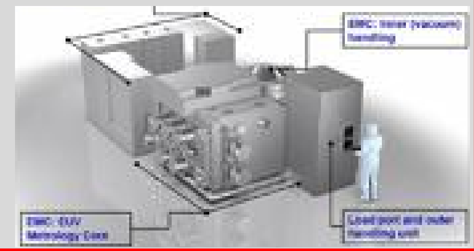
Precise machining/material modification using fs fiber laser

- Surface or sub-surface
- Cleaner cuts with fs
- Soft/hard materials
- Deep trenches

Mask inspection @ 13.5nm

- Coherent beam -> higher resolution (<12.6nm)
- Wavelength agile, adjustable penetration depth
- Image buried layers -> overlay metrology
- X10-100 faster, x1000 lower cost/image vs Zeiss AIMS®
- Technology scalable to 6.7nm and 1nm



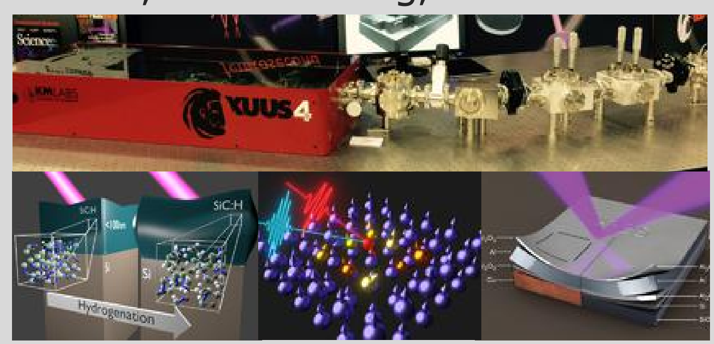


Patterned/bare wafer inspection

- Coherent laser-like beam
- Adjustable wavelength (DUV, VUV, EUV)
- Adjustable penetration depth
- Adjustable polarization (linear to circular)
- Quantitative elemental, chemical mapping
- Ultrasensitive to contaminants, roughness

Materials characterization

- Monitor in-situ growth: reflection/photoemission
- Thin films, elastic properties, ellipsometry
- Magnetic materials, band bending, band structure



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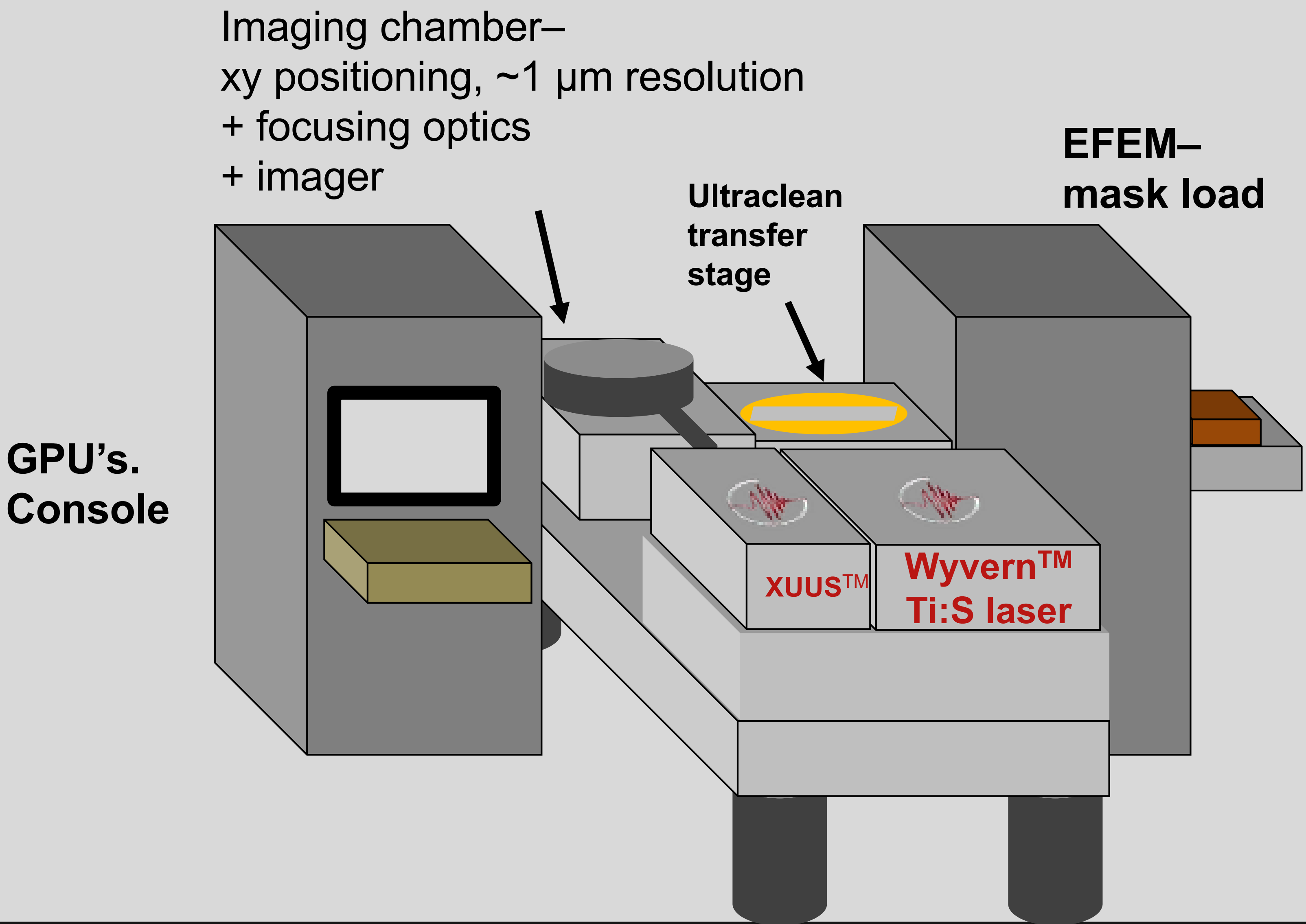
HHG CDI-based Actinic Mask Review Microscopy: feasibility analysis



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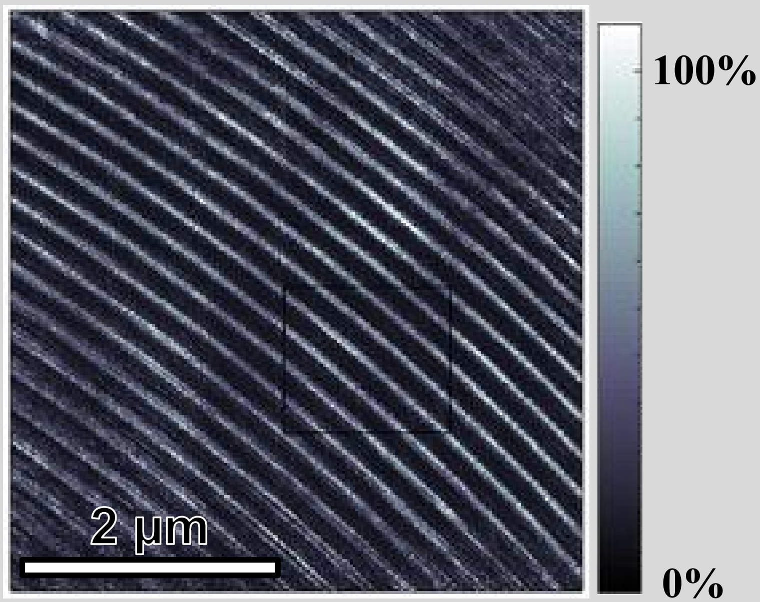
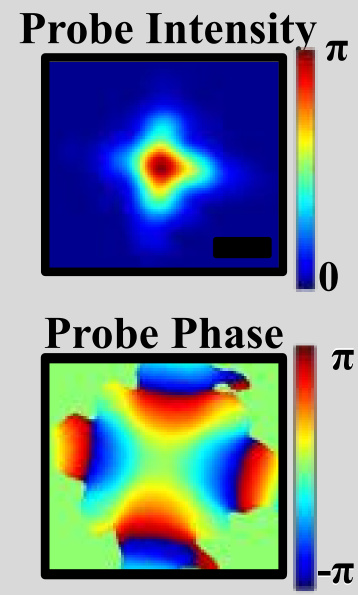
Imaging throughput– benchmark based on current work

- High contrast sample: transmission **T** of zone plate comparable to reflection **R** of mask
- Imaging throughput will be a function of:
  - Field of view
  - Required resolution
  - Required S/N





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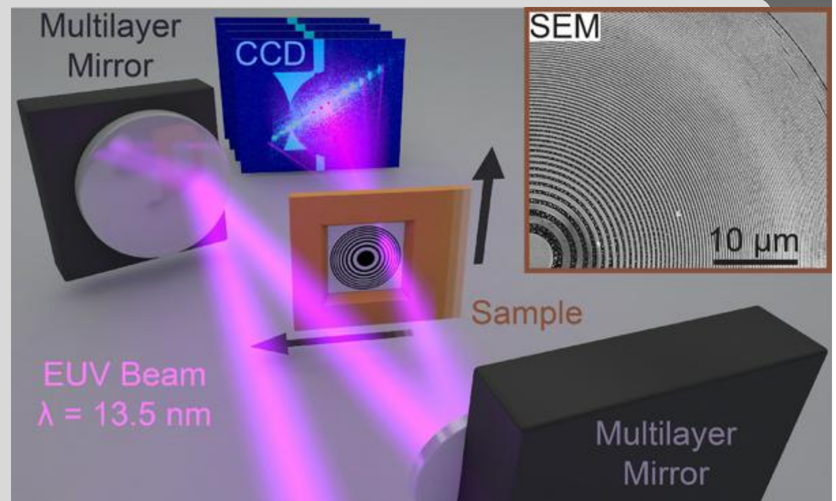
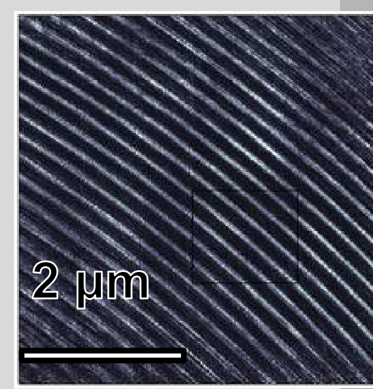
Current 13.5nm HHG CDI microscope throughput

- Spot size: <2 µm dia. (ω_0=0.75 µm)
- Laser:
  - 2 mJ, 3 kHz, 22 fs, 785 nm
  - 6 W average power
  - Prototype 13.5nm XUUS™
- 11x11 ptychographic scan (7µmx7µm)
- Exposure (2 frames/position): 9 sec
- Readout: 4.2 sec
- Exposure Time (Total): 18 min
- Full exposure readout time: 26 min
- ➔Current Imaging Rate (no optimization attempted):
  - **1 µm² / 30 sec @12.6nm resolution**





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Enhance XUUS™ source brightness

- Prototype 13.5nm XUUS™: 2.9×10^{10} ph/second at source
  - Single harmonic order at 92 eV
  - Source 5×10^{12} photons/sec/mm²/mrad² ; ~ 1 kW/mm²/sr
  - 6% measured efficiency of beamline

- 2×10^{9} ph/s, ~0.3 W cm^{-2} illumination on sample

- Near-term advances to yield **10-100x** flux improvement
  - Upgrade to XUUS™ with KMLabs' commercial specs
  - Improved beamline throughput
  - Increased drive laser power (6W → 30 W, same footprint, summer 2017)
  - Further gains by smart laser design

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Assumptions for CDI Actinic Mask Review throughput

- Assume XUUS™ source ~3x current flux
- Resolution 12 nm → 40 nm: reduce exposure time
  - 10x shorter exposure : 0.25 sec/position
- 5 x 5 scatter image matrix--> 6 sec exposure per location
- **Throughput ~1000 inspected positions per hour**
- **Increase x20 using known probe** (no ptychography scan)
  - *More than **10x** faster than current Zeiss AIMS®– in first generation!*
  - *Can be **100x** faster than current Zeiss AIMS®– in next generation!*
  - *More than **1000x** lower cost per image!*
  - *High harmonic source is not the limit!*

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Image acquisition speed: limited by imagers

- Image readout is the throughput limitation of current system
  - Currently >4.5 sec readout per acquisition position
  - Need to bring this to ~0.25 sec or faster
- Required speed is routine for visible imager sensors
    - i.e. iPhone 7, 3840 x 2160 @ 30 fps
- **Option 1:** sCMOS sensor (25-50 fps, 2048x2048)
  - In process of evaluating for EUV use
  - Relatively inexpensive, small
- **Option 2:** FAST CCD (100fps)
  - Developed by LBNL
  - Still expensive (~0.5M) , not "productized"

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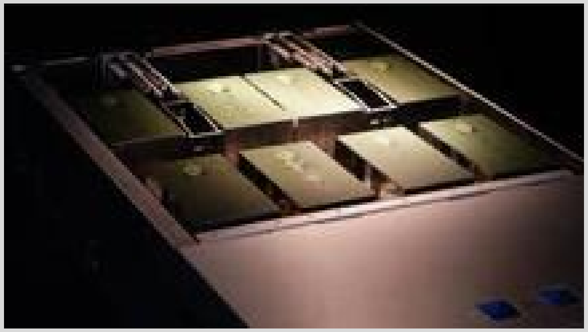
Image reconstruction throughput

- Use of MEP dramatically decreases time to reconstruction
- Current reconstruction speed: 1 GPU from 8-GPU NVIDIA DGX-1
  - 3 sec per iteration on 11x11 data set
  - Recognizable image after 5 iterations, best fit in ~100 iterations
- Scaling from 11x11 to 5x5:
  - ~3 seconds to recognizable image, ~1 min for high-resolution



- Computation not a serious limitation
  - Process images in parallel on separate GPU cores
  - 1000 high fidelity images per hour requires ~2x DGX-1
- Prior pattern knowledge can also be incorporated
  - Or, compare images in Fourier space, reconstruct only the defect
  - Use known EUV beam, need only 1 scatter pattern -> get x25 boost in speed!

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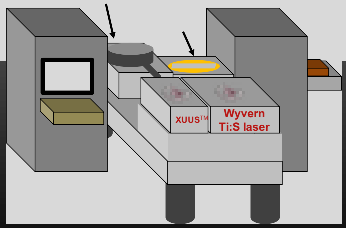
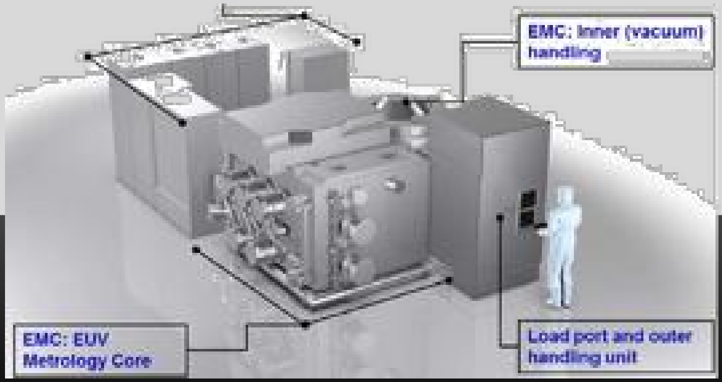
Comparison with Zeiss AIMS®

- Tabletop CDI Mask Review Microscope
  - Provides full characterization of EUV scattering properties of mask
  - Self calibrating, essentially no optical (mis)alignment
  - Allows for higher resolution, detailed amplitude and phase picture of surface/absorber structure
  - Computations can determine how a region will print
  - Small scale provides, for example, potential to integrate with mask repair tool
  - 1000 spots/hour, potential for >20,000/hour

- Zeiss AIMS®
  - Mimics illumination of scanner in detail
  - Image fidelity is a function of optical quality, system alignment
  - Throughput relatively slow at 50 spots/hour





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Opportunity to Partner

- Concept, subsystems, demo for EUV mask microscope have ***all*** been validated
  - Provides powerful capability complimentary to current tools
  - Based on advanced scatterometry – familiar to semi industry
  - Fully extensible to higher NA, shorter wavelengths, anamorphic systems, etc.
    - Simple, flexible optical system combined with software
  - Potential for broader application in nondestructive nano-imaging and metrology

- Development to-date was ***not*** through semi-industry funding
  - Current: DARPA SBIR Phase II program $1M
  - Other DARPA KMLabs/JILA
  - Indirect: STROBE Science and Technology Center (NSF), Intel Capital, etc.

- But **now** is the time to build, learn to use an EUVL mask tool based on CDI

- **Prototype CDI Actinic Mask Review tool cost ~$2-6M**

- **Timeline to prototype- 12-18 months** → Talk with KMLabs!

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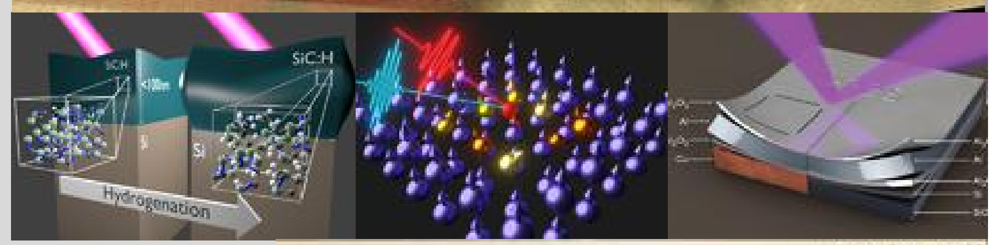
Other EUV XUUS™ applications

- In situ growth
- Overlay metrology
- Thin film characterization
- Dopant profiling
- Ellipsometry
- EUV optics reflectometer
- Interference litho for resists
- SEM-complement for chemical maps
- Imaging reflectometer

Y-Fi™ VUV



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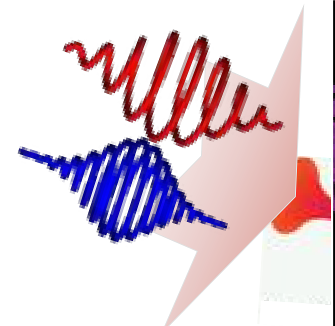
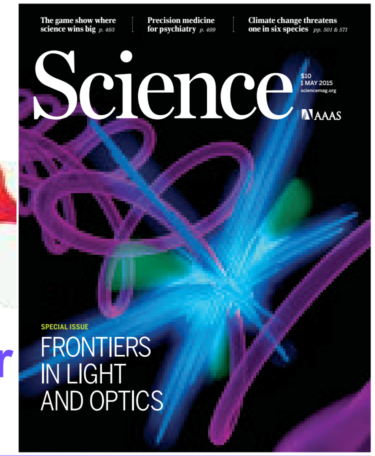
Exquisite quantum control over X-ray light by manipulating radiating electron wavefunction

- 12 octive supercontinuum or isolated peaks
- Full temporal coherence: femto to atto to zepto
- Full spatial coherence to keV
- Bright linear & circularly polarized HHG
- Unique light source better than we dreamed of!
- **Exquisite control of X-ray light using lasers**

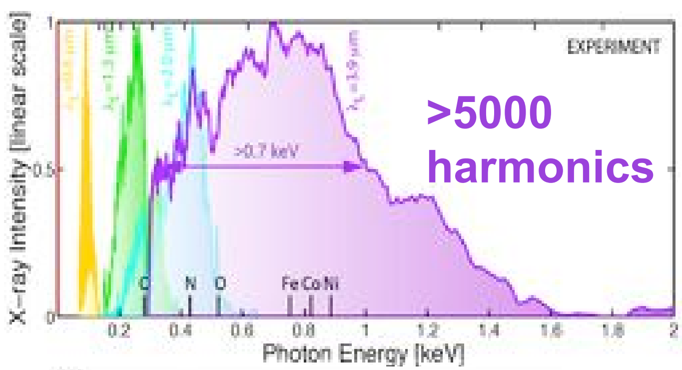
PNAS **112**, *14206 (2015); Nature Photonics* **9**, *99 (2015)*
Science Ad. **2**, *e1501333 (2016); Nature Photon.* **9**, *743*

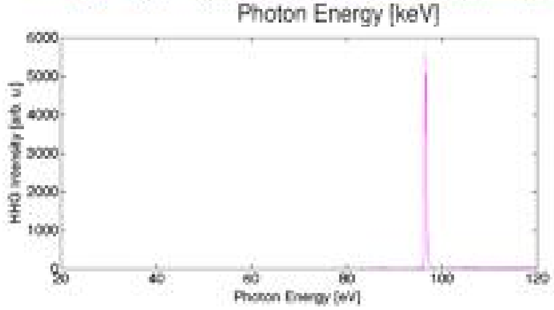




Linear/circular polarization

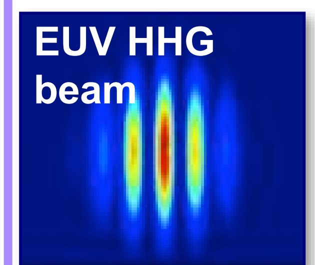
Broad coherent continuum OR Isolated single harmonic

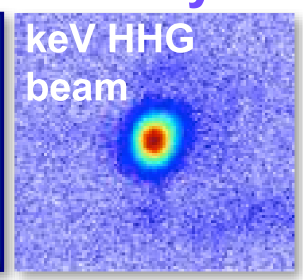


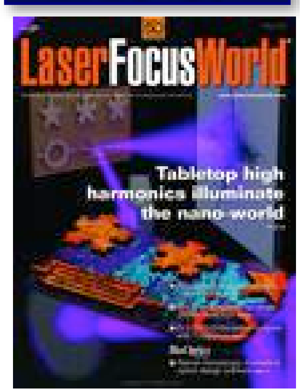


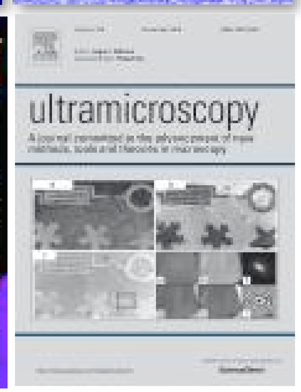
Science **336**, *1287 (2012); Science* **350**, *1225 (2015)*

Full spatial coherence: UV to soft X-ray



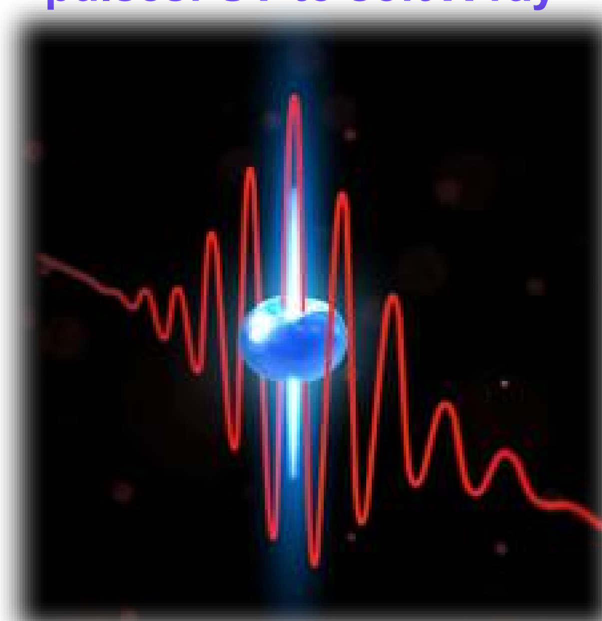






Science **297**, *376 ('02); Science* **348**, *530 ('15)*

Femtosecond to attosec pulses: UV to soft X-ray



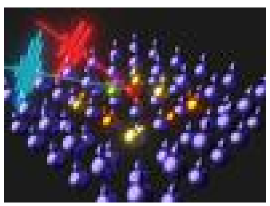
PRL **111**, *033002 (2013)*
PNAS **111**, *E2361 (2014)*

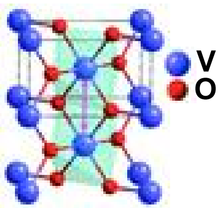
STROBE NSF STC on Real Time Functional Imaging: *STROBE.colorado.edu*

STROBE NSF SCIENCE AND TECHNOLOGY CENTER

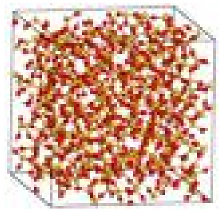
- **Advance** dynamic nano-imaging methods using electrons, X-rays and nano-probes
- **Integrate** to collectively provide new windows into functional nanosystems
- **Collaborate** to address important scientific and technological challenges

New windows into functional nanosystems


Energy materials

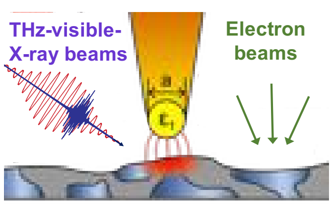


Quantum materials


Disordered materials

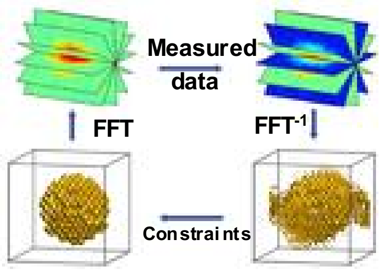

Biological materials

Advance and integrate dynamic imaging techniques

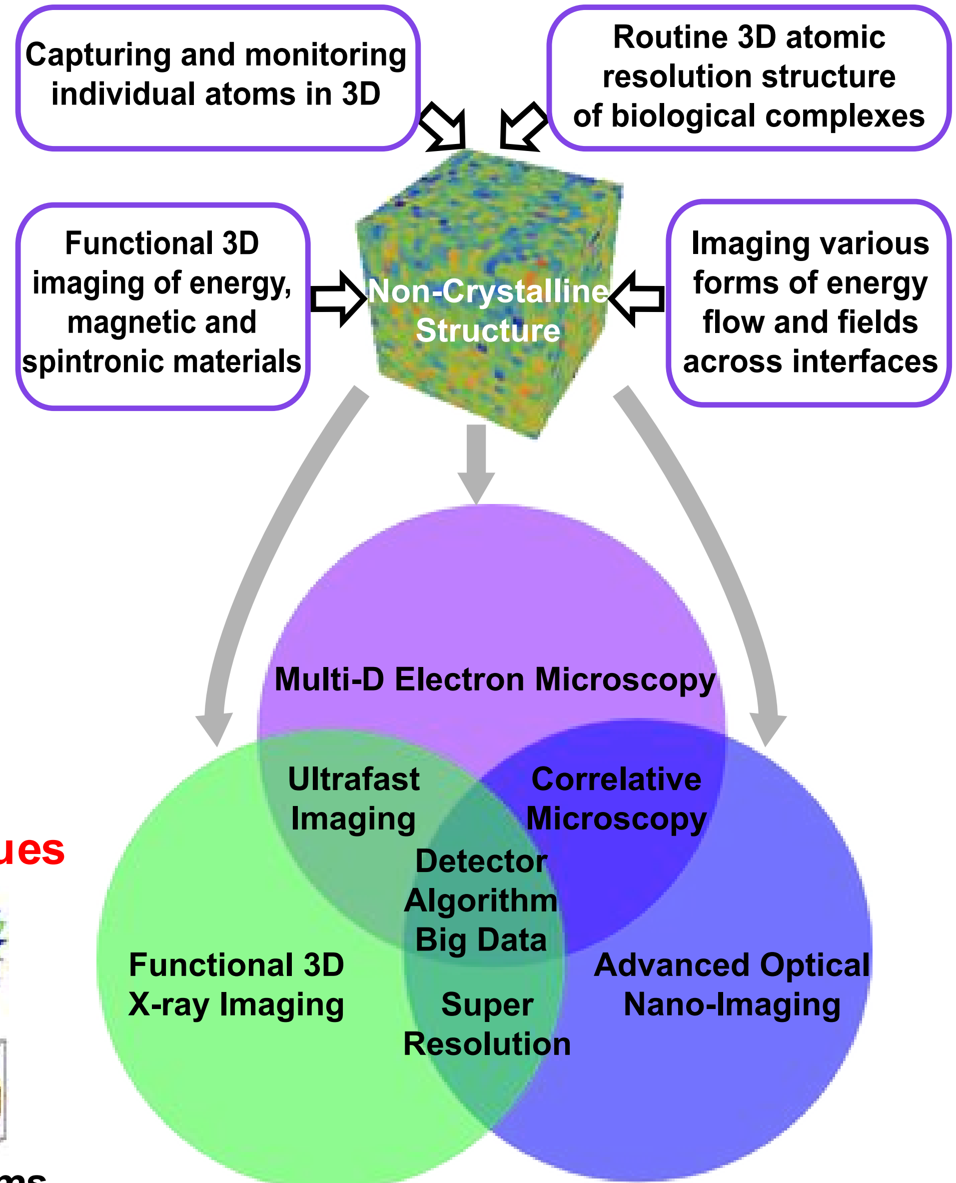


Techniques

Detectors, Big Data



Advanced Algorithms



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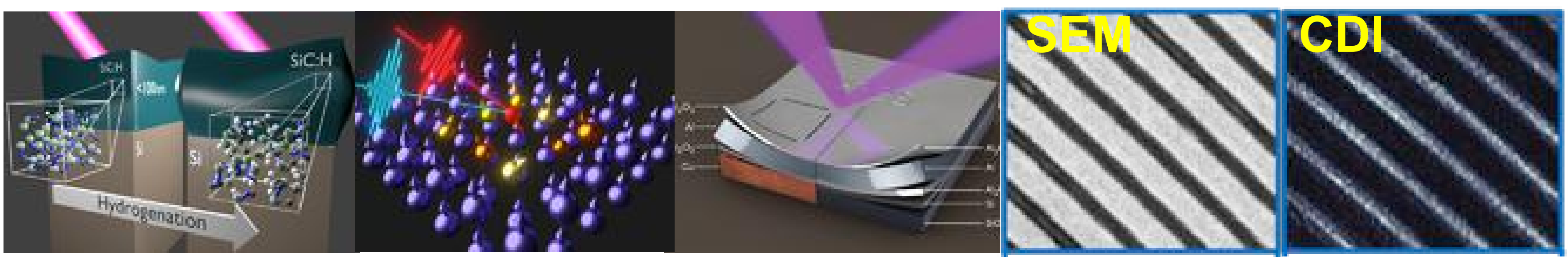
Summary

- High harmonic sources are a unique quantum technology allowing exquisite control over EUV and soft X-ray light on a tabletop

- HHG technology is already a useful tool for materials/chemical/nano
  - 1st 13.5 nm sub-wavelength EUV imaging
  - Inspection, dopant profiles, sub-surface imaging, contamination detection
  - Photoelectron & Photovoltage spectroscopies, In-situ materials growth monitor
  - Thin film metrology

- Bright future – everything scales with the wavelength

- The limits of HHG technology are not yet known: 10keV, 50keV?



VUV/EUV/SXR light science **Metrology** **Magnetics** **ARPES** **Imaging**