Topologically Structured Extreme Ultraviolet Beams with Designer Angular Momenta for Novel Magnetic Spectroscopies and Imaging

Kevin M. Dorney[1], Laura Rego[1], Nathan J. Brooks[1], Jennifer L. Ellis[1], Julio San Román[2], Chen-Ting Liao[1], Daniel D. Hickstein[1], Dmitriy Zusin[1], Christian Gentry[1], Emilio Pisanty[3], David E. Couch[1], Justin M. Shaw[4], Antonio Picón[2], Stefan Witte[5], Maciej Lewenstein[3], Luis Plaja[2], Carlos Hernández-García[2], Henry C. Kapteyn[1], and Margaret M. Murnane[1]

[1]*JILA - Department of Physics, University of Colorado and NIST, Boulder, Colorado, 80309, USA*

[2]*Grupo de Investigación en Aplicaciones del Láser y Fótonica, Departamento de Física Aplicada, Universidad de Salamanca, E-37008 Salamanca, Spain*

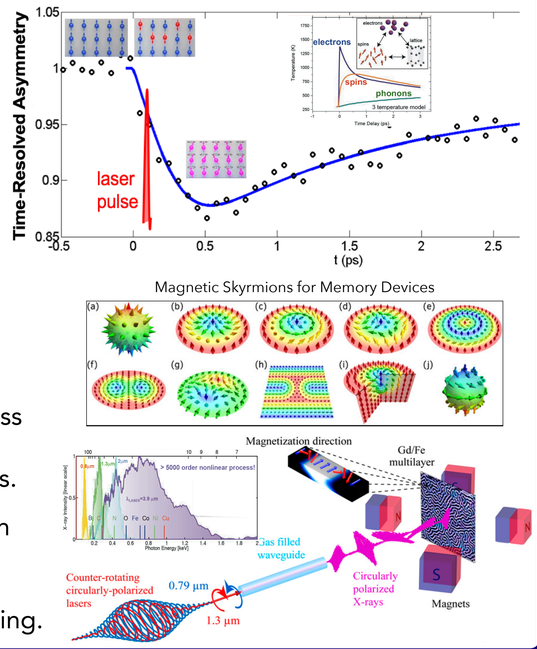
[3]*ICFO, Institut de Ciencies Fotoniques, Av. Carl Freidrich Gauss 3, 08860 Castelldefels (Barcelona), Spain*

[4]*Quantum Electromagnetics Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*

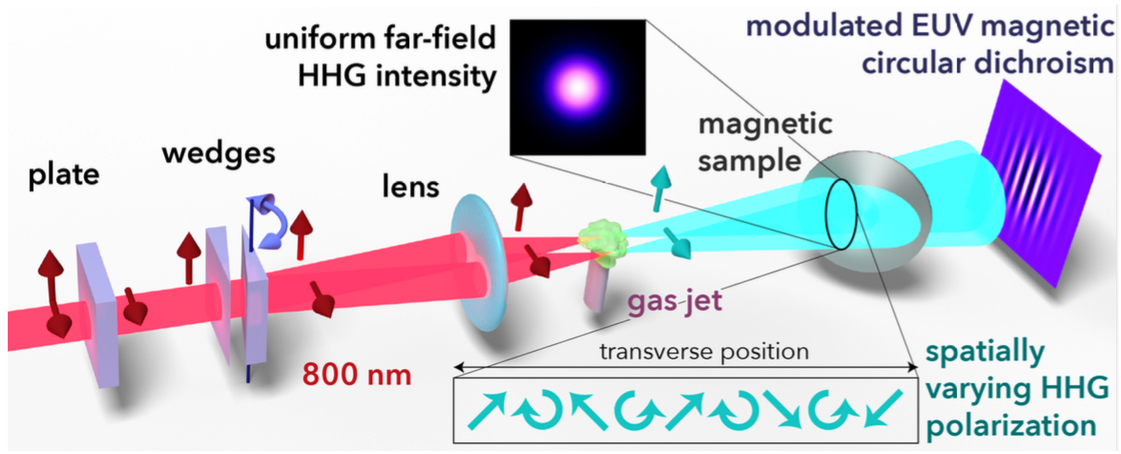
[5]*Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG Amsterdam, The Netherlands*

Abstract & Motivation

- **Motivation** - Lightwave-driven magnetism promises technologies such as petahertz spintronics[1] and optically readable/writable nanoscale magnetic memory devices[2]. Although promising, realization of these technologies has been hindered by a lack of a complete understanding of ultrafast (fs-ps)[3], nanoscale magneto-optical interactions.
- **Science Opportunity** - Resolving these processes demands spectroscopic and imaging modalities with element/spin specificty, few-fs time *and* few-nm spatial resolution. Extreme ultraviolet (EUV) and soft x-ray (SXR) light produced via high-harmonic generation (HHG) possess all of these qualities, making them promising sources for uncovering the intricate mechanisms of ultrafast magnetics.
- **Summary of Work** - By tailoring the HHG emission process, we realize novel, flexible, bright, tabletop-scale EUV light sources with non-trivial optical topologies for new avenues in magneto-optical spectroscopies and imaging.



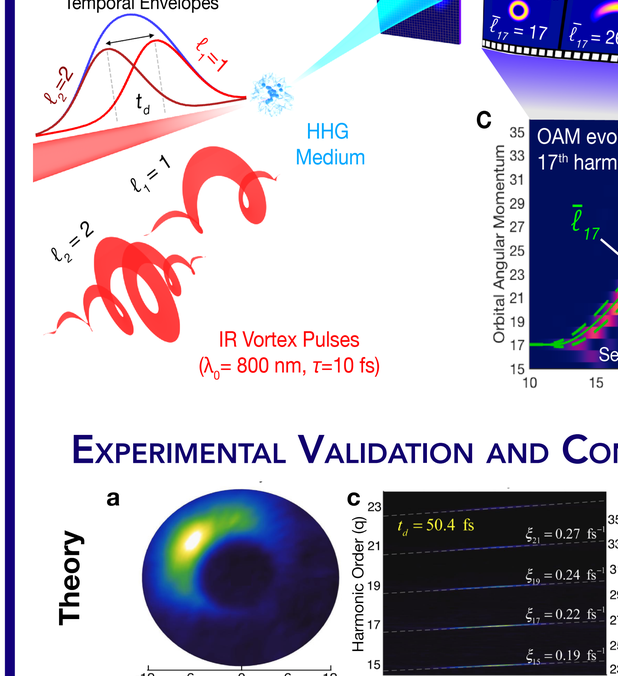
Optical Spin Gratings for Hyperspectral, Magnetic Imaging in the Extreme Ultraviolet[4]



A birefringent Fourier transform interferometer is employed to generate phase-locked EUV sources with orthogonal polarizations. The overlap of these sources generates an optical, EUV spin grating that can be exploited for quantitative, hyperspectral imaging of magnetic and chiral systems.

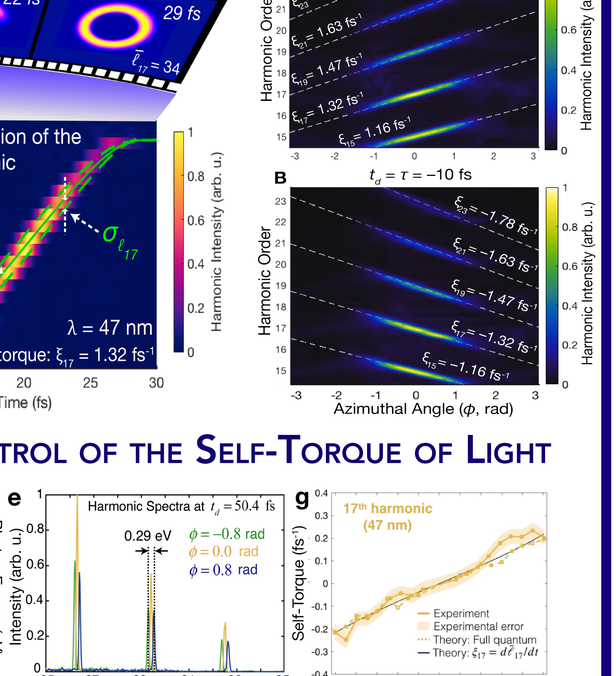
Spatially Resolved Spectroscopy of Magnetic Thin Films

$$A = \frac{(I_{M^+} - I_{M^-})}{(I_{M^+} + I_{M^-})} = \langle \sigma \rangle_{EUV} = \tanh(2 k_{EUV} \Delta\beta)$$

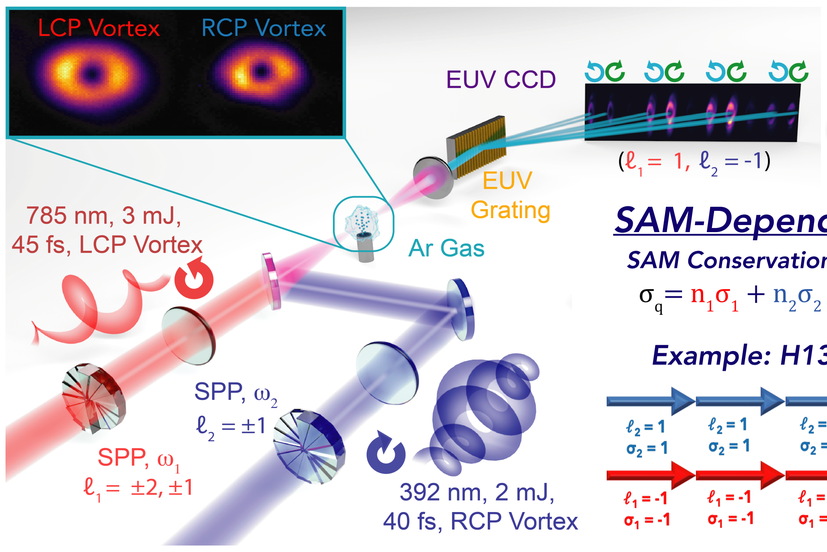


Hyperspectral Magnetic Spectroscopy and Imaging

- Scanning time-delay between the EUV sources yields an interferogram at each pixel
- Fourier inversion yields a hyperspectral map of the element-specific magnetic asymmetry



EUV Beams and Attosecond Pulses with Designer Spin and Orbital Angular Momentum[5]



SAM-Dependent Selection Rules[2,3]

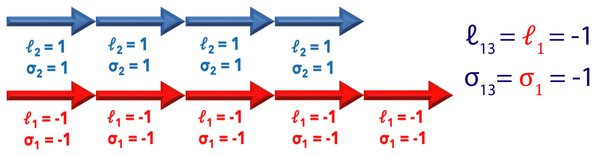
SAM Conservation

$$\sigma_q = n_1\sigma_1 + n_2\sigma_2$$

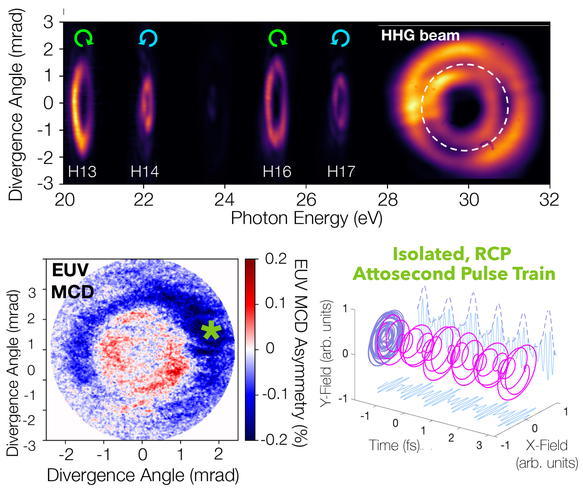
Parity Conservation

$$n_1 + n_2 = \text{odd}$$

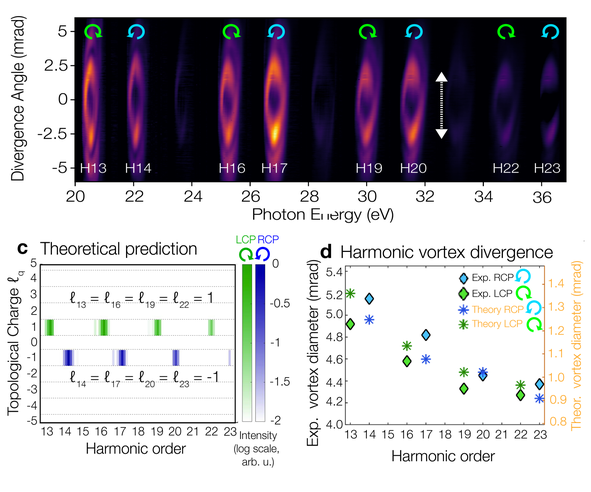
Example: H13 via $(\ell_1,\sigma_1 = -1, \ell_2,\sigma_2 = +1)$



Spatially Isolated, Attosecond Vortices with Opposite Helicities

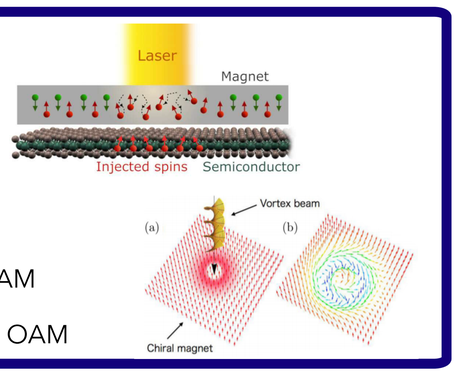


High Energy, Low OAM Attosecond Vortices



Conclusions & Outlook

Tabletop EUV light produced via HHG provides short-wavelength light with designer topologies for next generation magnetic spectroscopy and imaging of ultrafast, nanoscale spin dynamics.

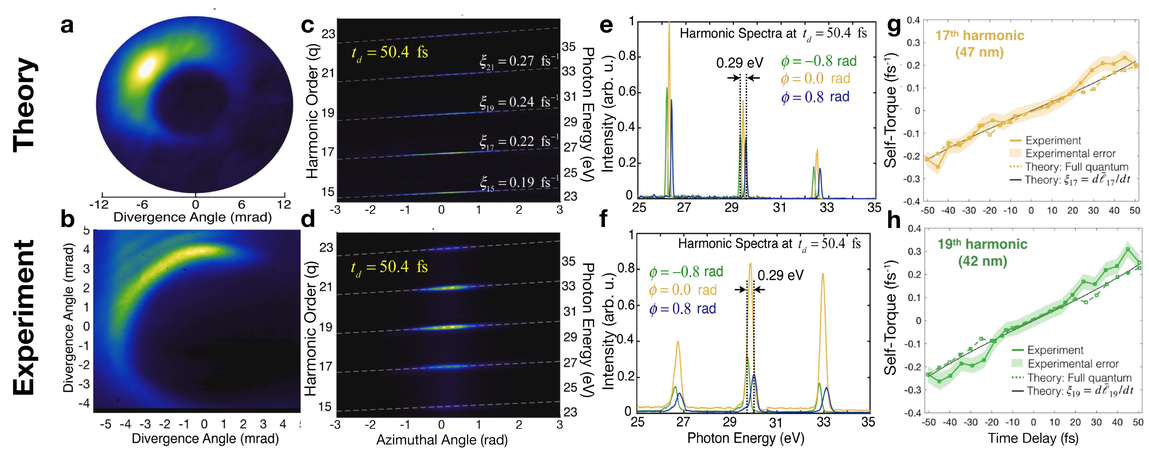


- EUV spin gratings for hyperspectral magnetic imaging
- EUV beams and attosecond pulses with Designer SAM and OAM
- EUV beams and attosecond pulses with dynamic, time-varying OAM

Attosecond Pulses with Time-Varying OAM: The Self-Torque of Light[6]

Driving the HHG process with a time-delayed vortex pulse pair yields EUV beams and attosecond pulses with a new optical property: time-varying OAM (the self-torque of light)

Experimental Validation and Control of the Self-Torque of Light



References

[1]Siegert, F. et al. *Nature* **571**, 240-244 (2019).

[2]Nagaosa, N. et al. *Nat. Nano.* **8**, 899-911 (2013).

[3]Tengdin, P. et al. *Sci. Adv.* **4**, eaap9744 (2019).

[4]Ellis, et al. *Optica* **5**, 479-485 (2018).

[5]Dorney, K. M. et al. *Nat. Photoni.* **13**, 123-130 (2019).

[6]Rego, L. et al. *Science* **364**, eaaw9486 (2019).