REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
16-02-2017	Final Report	1-Sep-2013 - 31-Aug-2016

4. TITLE AND SUBTITLE
Final Report: Photon Energy Limits of Bright High Harmonic X-Ray Generation

5a. CONTRACT NUMBER
W911NF-13-1-0259

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
63842-EL.7

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The goal of this research effort is to explore the fundamental quantum physics and phase matching limits of high harmonic generation (HHG) in the multi-keV spectral region. The understanding developed as a result of this work will make it possible to identify the best path forward for future experiments in generating bright coherent hard X-ray beams in the 10 keV range and greater using a tabletop-scale aparatus. This capability promises revolutionary advances in remote sensing through use of well-directed, penetrating hard X-ray radiation with extremely low beam

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Margaret Murnane
UU	UU	UU	UU		19b. TELEPHONE NUMBER 303-492-7839

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Photon Energy Limits of Bright High Harmonic X-Ray Generation

ABSTRACT

The goal of this research effort is to explore the fundamental quantum physics and phase matching limits of high harmonic generation (HHG) in the multi-keV spectral region. The understanding developed as a result of this work will make it possible to identify the best path forward for future experiments in generating bright coherent hard X-ray beams in the 10 keV range and greater using a tabletop-scale aparatus. This capability promises revolutionary advances in remote sensing through use of well-directed, penetrating hard X-ray radiation with extremely low beam divergence, and also in dynamic imaging of fucnition in thick samples at the spatio-temporal resolution extreme for current and next-generation nanotechnology and medical imaging.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/15/2017	3	1. D. Popmintchev, C. Hernández-García, F. Dollar, C. Mancuso, J. Pérez-Hernández, M.C. Chen, A. Hankla, X. Gao, B. Shim, A. Gaeta, M. Tarazkar, D. Romanov, R. Levis, J. Gaffney, M. Foord, S. Libby, A. Jaron-Becker, A. Becker, L. Plaja, M. Murnane, H. Kapteyn, T. Popmintchev. Efficient soft X-ray high harmonic generation in multiply-ionized plasmas: the ultraviolet surprise, Science, (07 2015): 1225. doi: 366,075.00
02/16/2017	4	Benjamin R. Galloway, Dimitar Popmintchev, Emilio Pisanty, Daniel D. Hickstein, Margaret M. Murnane, Henry C. Kapteyn, Tenio Popmintchev. Lorentz drift compensation in high harmonic generation in the soft and hard X-ray regions of the spectrum, Optics Express, ( ): 21818. doi: 1,029,780.00
02/16/2017	6	D. Popmintchev, C. Hernandez-Garcia, F. Dollar, C. Mancuso, J. A. Perez-Hernandez, M.-C. Chen, A. Hankla, X. Gao, B. Shim, A. L. Gaeta, M. Tarazkar, D. A. Romanov, R. J. Levis, J. A. Gaffney, M. Foord, S. B. Libby, A. Jaron-Becker, A. Becker, L. Plaja, M. M. Murnane, H. C. Kapteyn, T. Popmintchev. Ultraviolet surprise: Efficient soft x-ray high-harmonic generation in multiply ionized plasmas, Science, ( ): 1225. doi: 1,029,782.00

TOTAL: **3**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/25/2014	1	Dimitar Popmintchev, Carlos Hernandez-Garcia, Bonggu Shim, Ming-Chang Chen, Franklin Dollar, Christopher A. Mancuso, Jose Pérez- Hernández, Xiaohui Gao, Amelia Hankla, Alexander L. Gaeta, Maryam Tarazkar, Dmitri Romanov, Robert Levis, Agnieszka Jaron-Becker, Andreas Becker, Luis Plaja, Margaret Murnane, Henry Kapteyn, Tenio Popmintchev . Bright High Order Harmonic Generation in a MultiplyIonized Plasma up to the Water Window, CLEO: QELS_Fundamental Science. 09-JUN-14, . : ,

TOTAL: 1

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/31/2015	2.00	Carlos Hernandez-Garcia, Tenio Popmintchev, Margaret Murnane, Henry Kapteyn, Luis Plaja, Agnieszka Jaron-Becker, Andreas Becker. Group-velocity mismatch effect in high-order harmonicgeneration, CLEO Technical Digest (05 2015)

TOTAL: 1

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Generation of VUV, EUV, and X-ray Light Using VUV-UV-VIS Lasers

Patents Awarded

Generation of VUV, EUV, and X-ray Light Using VUV-UV-VIS Lasers

Awards

2015 American Indian Science and Engineering Society Most Promising Scientist or Engineer Award (Franklin Dollar)
2016 IUPAP Young Scientist Award (Tenio Popmintchev)
2016 Honorary Degree of Doctor of Science, Uppsala University, Sweden (Margaret Murnane)
2015 Elected to Member, American Philosophical Society (Margaret Murnane)
2015 Honorary Degree of Doctor of Science, University College Dublin (Margaret Murnane)
2015 Honorary Degree of Doctor of Science, Trinity College Dublin (Margaret Murnane)
2014 Moore Foundation Experimental Investigator Award (Margaret Murnane)
2014 CU Boulder Inventor of the Year (shared between Henry Kapteyn and Margaret Murnane)
2013 Honorary Member, Royal Irish Academy (Margaret Murnane)

Graduate Students

NAME	PERCENT_SUPPORTED	DISCIPLINE
Benjamin Galloway	0	Physics
Tingting Fan	50	Physics
Dimitar Popmintchev	30	Physics
FTE Equivalent:	**0.80**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Dr. Tenio Popmintchev	0.50
Dr. Seth Cousin	0.25
Dr. Michael Gerrity	0.25
Dr. Franklin Dollar	0.25
FTE Equivalent:	**1.25**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Margaret Murnane	0.00	Yes
Henry Kapteyn	0.00	Yes
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Dimitar Popmintchev	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

5 **Generation of VUV, EUV, and X-ray Light Using VUV-UV-VIS Lasers**

Patent Filed in US? (5d-1) Y
Patent Filed in Foreign Countries? (5d-2) N
Was the assignment forwarded to the contracting officer? (5e) Y
Foreign Countries of application (5g-2):

5a: T. Popmintchev
5f-1a:
5f-c:

5a: H. Kapteyn
5f-1a:
5f-c:

5a: M. M. Murnane
5f-1a:
5f-c:

5a: D. Popmintchev
5f-1a:
5f-c:

Scientific Progress

Technology Transfer

ANNUAL TECHNICAL REPORT

Period covered by report: September 01, 2014 and ending August 30, 2016.

Proposal Title: Photon Energy Limits of Bright High Harmonic X-Ray Generation

Contract/Grant number: W911NF-13-1-0259

ARO Program Manager: DOD Army ARO, Dr. James Harvey, E-mail: james.harvey@osd.mil or james.f.harvey.civ@mail.mil

Author(s) of report: Margaret Murnane and Henry Kapteyn

Performing Organization Name(s) and Address(es): JILA, Department of Physics, University of Colorado at Boulder, Boulder, CO 80309

ARO proposal number: 63842EL

People supported:

(2) Student/Supported Personnel Metrics **for this Reporting Period** (name, % supported, %Full Time Equivalent (FTE) support provided by this agreement, and total for each category):

(a) Graduate Students:
Benjamin Galloway, Tingting Fan, Dimitar Popmintchev

(b) Research Scientists, Post Doctorates: Dr. Tenio Popmintchev, Dr. Seth Cousin, Dr. Michael Gerrity, Dr. Franklin Dollar

(c) Faculty: Margaret Murnane and Henry Kapteyn, no support

(d) Undergraduate Students:

(e) Graduating Undergraduate Metrics (funded by this agreement and graduating during this reporting period):
i. Number who graduated during this period : 0
ii. Number who graduated during this period with a degree in science, mathematics, engineering, or technology fields : 0
iii. Number who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: 0
iv. Number who achieved a 3.5 GPA to 4.0 (4.0 max scale); 0
v. Number funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0
vi. Number who intend to work for the Department of Defense:
vii. Number who will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields

(f) Masters Degrees Awarded (Name of each, Total #): None

(g) Ph.D.s Awarded (Name of each, Total #): 1 (Dimitar Popmintchev)

(h) Other Research staff (Name of each, FTE % Supported for each, Total % Supported):
None

Photon Energy Limits of Bright High Harmonic X-Ray Generation

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The goal of this research effort is to explore the fundamental quantum physics and phase matching limits of high harmonic generation (HHG) in the multi-keV spectral region. The understanding developed as a result of this work will make it possible to identify the best path forward for future experiments in generating bright coherent hard X-ray beams in the 10 keV range and greater using a tabletop-scale aparatus. This capability promises revolutionary advances in remote sensing through use of well-directed, penetrating hard X-ray radiation with extremely low beam divergence, and also in dynamic imaging of fucnition in thick samples at the spatio-temporal resolution extreme for current and next-generation nanotechnology and medical imaging.

At the start of this research effort, the two most promising approaches for generating HHG in the multi-keV region were:

1) Phase matched HHG using mid-infrared (IR) driving lasers and gently ionized gas atoms.
2) All-optical quasi phase matching (QPM) of HHG at higher ionization levels of the neutral atomic media.

During this grant, we discovered two exciting and important new aspects of HHG:

3) There is a third unexpected and exciting HHG scheme that generates bright soft X-ray high harmonics, where the photon energy limits are also not known. This approaches uses intense ultraviolet (UV) lasers to generate HHG in multiply charged plasmas. This unexpected new finding was published in Science, with a patent also awarded.[1, 2]
4) We also identified that the HHG yield per atom does not drop as rapidly as expected due to magnetic field effects, as the driving laser wavelength in increased to 2 µm and longer. The presence of a wave guide HHG geometry helps to mitigate the Lorentz drift, and the X-ray beam profile becomes highly symmetric instead of being distorted.[3]

Background

The major advantage of mid-IR laser driven HHG is that by increasing the laser wavelength, the maximum HHG photon energy that can be generated by each atom also increases: $h\nu_{single\ atom} \sim I_L \lambda_L^2$ where I_L and λ_L are the laser intensity and wavelength. And simultaneously, the limit of phase matching also increases very strongly, nearly quadratically: $h\nu_{phase\ matching} \sim I_L \lambda_L^{1.7}$. We had demonstrated experimentally that using 4 µm lasers, phase matching could be extended into the keV soft X-ray region of >1.6 keV. Interestingly, the generated X-ray spectra exhibit supercontiuum spectral structure (i.e. a "coherent X-ray white light" beam). Using longer wavelength >8-10 µm lasers, we expect to extend HHG into the ≈ 10 keV hard X-ray region. However, the long time the electron spends in the continuum when a long-period mid-IR driving laser is used results in significant quantum diffusion of the electron wavefunction, and hence, lower emission per atom. Thus, an additional physical mechanism or a new scheme is required to mitigate this fundamental quantum physics effect. Furthermore, multi-millijoule lasers with wavelengths >8 µm are also not yet available to explore experimentally the scaling of the phase matched HHG flux. Also, even the best state-of-the-art computer clusters cannot model coherent HHG build-up under such extreme upconversion conditions (>5000th harmonic order at 1.6 keV, or >300000th order at 20 keV).

The second most promising route towards multi-keV X-ray HHG is all-optical QPM which has the advantage of selectively enhancing an HHG spectral band in the X-ray region and focus on sensing of specific elements in nano and bio targets. This scheme had been experimentally demonstrated by our group upto photon energies >0.15 keV using only near-IR drivers. We also developed theoretical schemes that extended QPM HHG well into the multi-keV regime. However, QPM is challenging to implement because two or more driving laser beams of various wavelengths are required. Also in contrast to perturbative low order harmonic generation in periodic crystals, the HHG coherent zones in plasmas vary in length along the direction of laser propagation and can also shift in space making it challenging to optimize.

The third route of effectively phase matched HHG using UV driving lasers compliments the first two schemes in the spectral and temporal domains. The UV-driven soft X-ray harmonics have a comb spectral structure with very narrow linewidths ideal for high resolution imaging. In the time domain, the X-rays emerge as a train of large number of pulses that boost the HHG flux, in contrast to mid-IR driven HHG where only one bright X-ray burst can be phase matched.

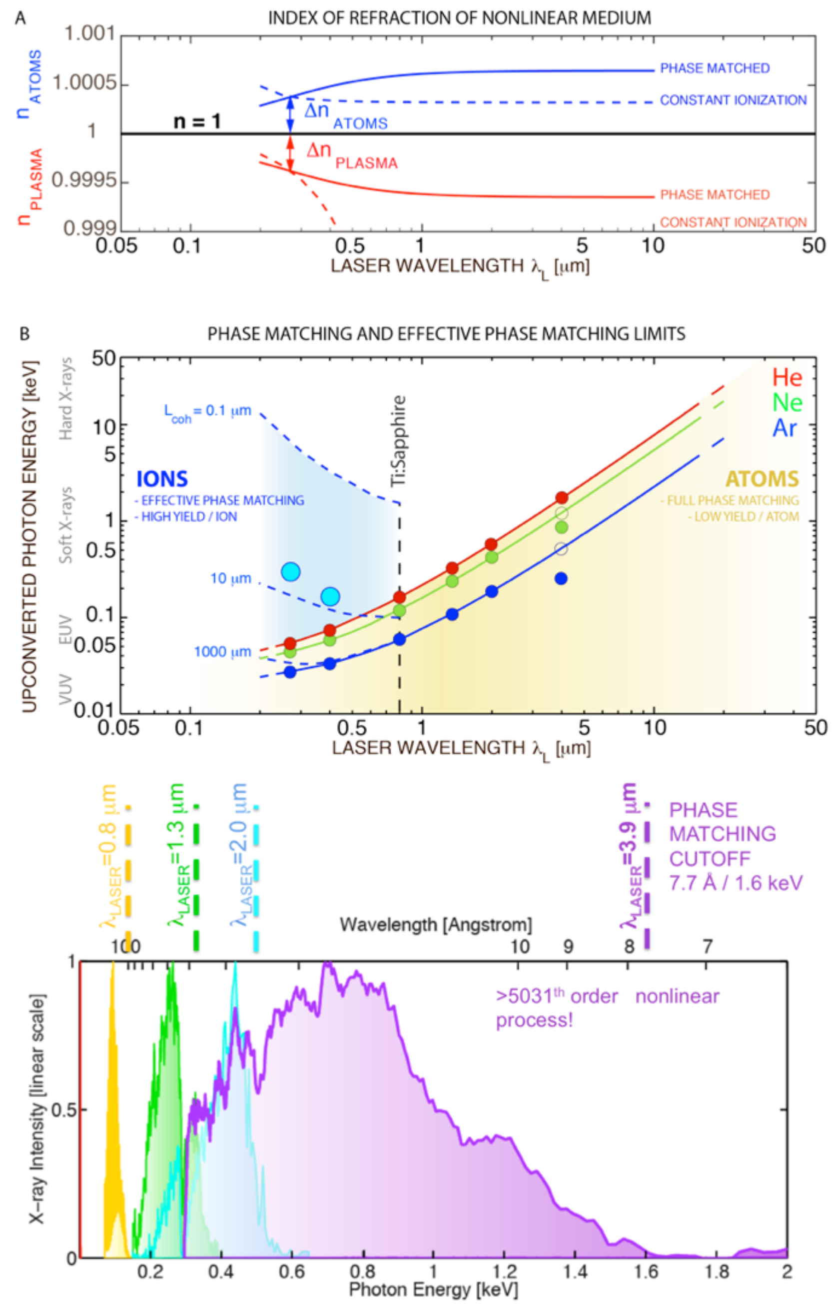

Fig. 1. (A) While each atom of the nonlinear medium can emit HHG up to high photon energies, the phase matching photon energy limits for bright emission from many atoms are dictated by the dynamically changing index of refraction of the medium. The balance between the index of refraction of the neutral atoms and the plasma sets a limit on the maximum laser intensity that can be used for each laser color. (B) As the driving laser wavelength increases from the UV into the mid-IR region, the full phase matching limits for bright HHG emission move to higher photon energies. Solid lines show theoretical models that have not been validated beyond 4 μm driving wavelengths. Solid circles show where phase matching has been demonstrated experimentally. Alternatively, combining very intense UV driving-lasers and multiply charged ions can also result in bright X-ray HHG emission that is predicted to scale into the keV regime. (C) Experimental X-ray supercontinuum HHG from neutral atoms broaden and extend to shorter wavelengths as the laser wavelength is increased.

Highlights from Grant: We made advances in two areas:

1. <u>Theoretical scaling of effective phase matching limits of UV-driven HHG in the spectral and temporal domains:</u> In a new regime, which was recently patented and published in Science [1, 2], we demonstrated that by driving HHG with intense UV lasers, we can increase the conversion efficiency throughout the VUV, EUV, and soft X-ray regions of the spectrum. It is well established that the low quantum diffusion of the radiating electron wavepacket for shorter wavelength UV driving lasers maximizes the single-atom yield. However, in this new regime of intense UV-driven HHG, the macroscopic phase matched buildup also becomes favorable. Unexpectedly, the higher linear and nonlinear indices of large atoms and ions can contribute significantly to the dispersion experienced by the driving laser, and serve to counteract large plasma dispersion (see Fig. 2). Moreover, low group velocity walk-off as well as slowly-varying phase matching conditions means that group and phase velocity matching is possible over many cycles of the laser. This enables good coherent build-up of the HHG signal, for the first time, in multiply-ionized plasmas at very high gas pressures, extending to photon energies ~300 eV (see Fig. 2). This interpretation is evidenced by the high conversion into single harmonics in the vacuum UV and soft X-ray regions from 10^{-3} - 10^{-7}, which are orders of magnitude brighter than has been observed to date from ions. In fact, the efficiencies in the VUV-EUV are higher than have been observed using any other approach to date. The well-separated narrowband HHG peaks, with record narrow linewidths of $\lambda/\Delta\lambda$ ~ 450 in the VUV to soft X-ray regions, are ideal for applications in dynamic imaging and photoelectron spectroscopies.

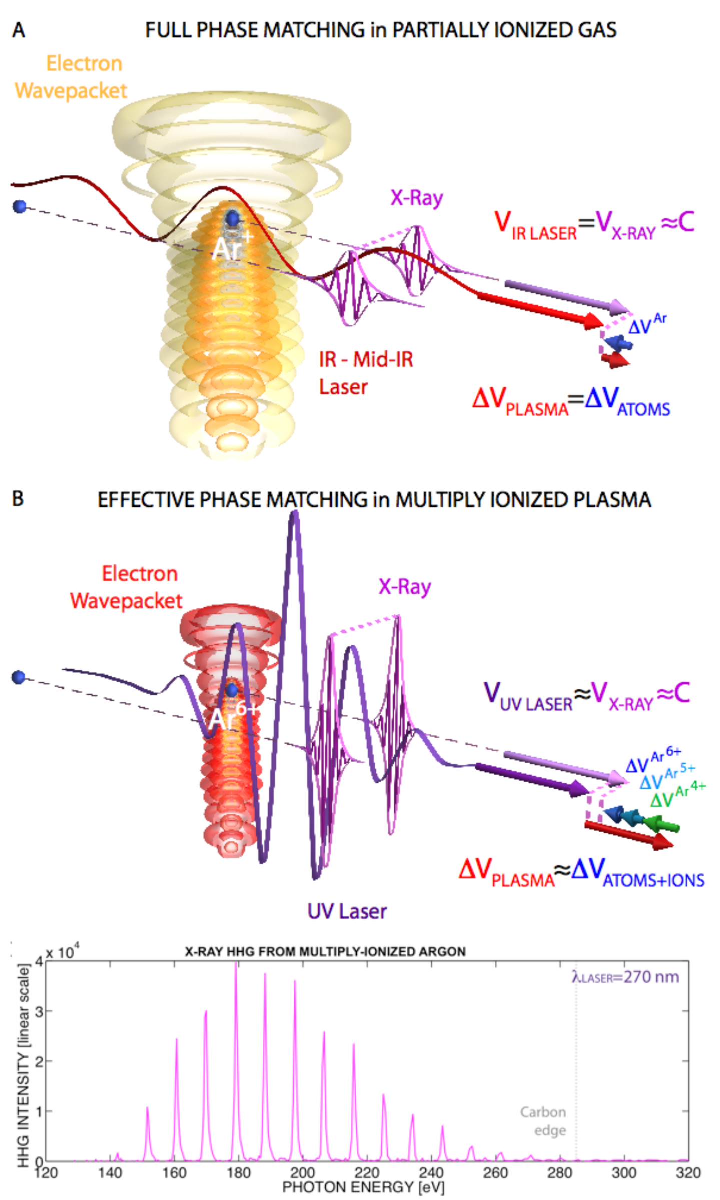

Fig. 2. Comparison of phase-matched HHG for mid-IR and UV driving lasers. (A) Conventional phase matching of HHG using an 0.8μm laser: the linear dispersion of atoms balances plasma dispersion at very low ionization, to equalize phase velocities of the laser and HHG fields. Δv is the offset from *c*, the speed of light. (B) For UV lasers, the high linear and nonlinear indices of atoms *and* ions balance the relatively low plasma dispersion, ensuring a long coherence length even in the case of ~5x ionized gas. The lower transverse quantum diffusion of the electron wavefunction for UV lasers enhances the microscopic HHG yield. The characteristic X-ray spectra show discrete harmonics with very narrow linewidths using UV drivers in contrast to using mid-IR lasers.

Under this grant, to quantitatively explain why bright harmonics from Ar driven by UV lasers can extend into the soft X-ray region, we used simple numerical models, which have been extensively validated for near and mid-IR driving lasers, as well as exact integration of the time-dependent Schrodinger equation. To aid with physical insight, Fig. 1A (dashed lines) plots the calculated index of refraction contribution of an Ar atom compared with that of a free electron. As expected, the refractive indices of neutral atoms are largest in the UV region of the spectrum. On the other hand, the free electron plasma contribution to the refractive index scales as –

$$n_{plasma} = \sqrt{1 - \omega_p^2/\omega_{Laser}^2}, \text{ where } \omega_p = \sqrt{n_e e^2/m_e \varepsilon_0},$$

and where ω_p is the plasma frequency corresponding to an electron density n_e, and where e and m_e are the charge and mass of the electron. Hence, lower frequencies (i.e. longer laser wavelengths) will experience much higher plasma dispersion, and therefore phase matching occurs only at low ionization levels, that are below the critical ionization.

In contrast, for wavelengths in the visible and UV spectral regions, *the positive refractive index contribution of a neutral Ar atom exceeds the negative contribution of a free electron.* This corresponds to a critical ionization level ≈ 40% for UV-driven HHG at ~40 eV. Moreover, the refractive indices of *ions* in the UV are comparable to that of neutral Ar, since the ionization potential of each successive ionization stage is increasing only modestly. Thus, for UV driving lasers, good buildup of the HHG signal is possible even in a multiply ionized plasma. This enables a new regime of effective phase matching extending into the soft X-ray region, and in theory even to hard X-rays. Note that for UV-driven HHG, full phase matching is possible in the VUV- EUV, while efficient HHG is possible in soft X-ray region at high pressures.

In collaboration with a group at LLNL, we also investigated the transparency of the multiply charged plasma. Decreased medium opacity due to removing several valence electrons can also increase the yield, particularly for intense UV-driven HHG, where the single-atom yield is already very high. However, we calculate that increasing transparency of the medium is not sufficient to explain the observed increase in HHG yield, especially when the coherence length is smaller than the absorption length. Thus, in the future, all-optical quasi-phase matching HHG techniques could take advantage of the full X-ray absorption length to enhance the yield further.

Under this grant we also studied theoretically the temporal properties of the UV-driven harmonics for ultrafast dynamic imaging. In contrast to the strongly-chirped HHG emission driven by near and mid-IR driving lasers, calculations show that HHG driven by UV is particularly suitable for generating nearly transform-limited attosecond bursts (or pulse trains), with very low temporal chirp that should be straightforward to compensate. It is already known that the atto-chirp of each individual attosecond burst will be reduced as the driving laser wavelength is reduced in the UV, due to the shorter time the electron spends in the continuum (≈ 300 as). However, for higher photon energies using more intense UV driving lasers, the pulse duration and atto-chirp will reduce even further due to the larger phase matched bandwidth. In the case of UV driving lasers, the duration of the highest harmonics naturally emerge as slightly chirped ~105 *as* pulses, compared with a strongly chirped 325 *as* pulses for an 0.8 μm driving laser in the same photon energy range. For comparison, for 2 - 4 μm mid-IR driven HHG, the emission is brightest when the HHG pulse emerges as an isolated, very strongly chirped, 300 - 1200 *as* burst. The experimental HHG emission from Ar in Fig. 2 is predicted to emerge as a long 10 fs train of near-transform-limited ~100 attosecond pulses, eliminating the need for any X-ray post-compression techniques that are lossy and bandwidth limited.

2. Lorentz Force Drift and Electron Wavepacket Spread for Very Intense UV Drivers: To achieve the brightest harmonics possible at any driving laser wavelength, the probability of the electron to recombine with its parent ion must also be maximized. As our past analysis have shown, phase-matched HHG emission using mid-IR driving lasers scales well into the hard X-ray regime of >10-20 keV (see Fig. 1) while still requiring nonrelativistic laser intensities of 10^{14} - 10^{15} W/cm^2. However, the B-field component of the ponderomotive force cannot be neglected because the excursion time for the recolliding electron is also increasing with longer driving laser wavelengths. Fortunately, in the absence of any other external fields, the electron wavepacket drifts along the laser propagation direction to a distance that is smaller that the wavepacket spread due to quantum diffusion. For example, for a 9 µm driving laser and a phase matching intensity of 3x10^{14} W/cm^2, the electron fluence at the site of the atom drops 10x due to this drift, which reduces the single-atom HHG efficiency.

Under this grant, we studied the highest HHG photon energy as a function of the color of the laser using peak intensities where the electron fluence at the site of the atom drops on the scale of 1/e to 1/e^2. Under such conditions there is still a significant overlap between the rescattring electron wave function and the wave function in the ground state. Surprisingly, the electron wavepacket spread for 0.2 µm UV driver can be greater than the drift induced by the Lorentz force even for very high photon energies well into the hard X-ray spectral region of >80-120 keV, allowing for strong recombination propability. The same fluence of the electron at the site of the atom is reached at a photon energy limit of >9 keV for a 10 µm mid-IR driver. This intriguing result suggests that the fundamental rescattering physics of the HHG process does not terminate the HHG emission from a single atom even at very high UV laser intensities required to reach the hard X-ray region.

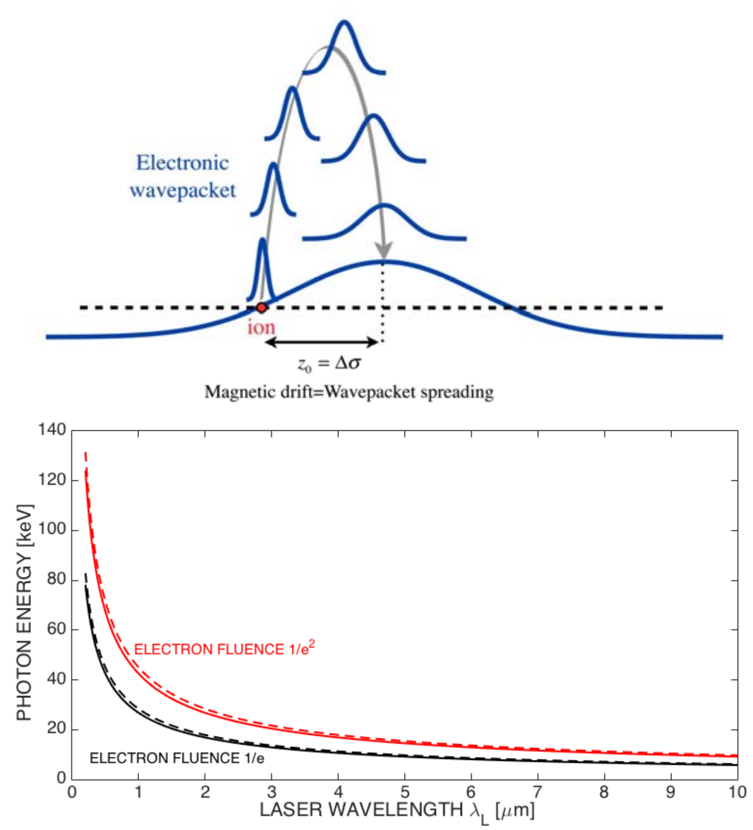

Fig. 3. (Top) Electron rescattering under the influence of the full electromagnetic field where the magnetic filed contribution in the Lorentz force results in a drift z_0 of the wavepacket along the direction of laser propagation from left to right. HHG emission is possible if the quantum diffusion results in an wavepacket spread $\Delta\sigma \sim z_0$ that allows for high recombination probability. (Bottom) Maximum HHG photon energy for UV to mid-IR lasers at peak intensities where the electron fluence at the site of the ion drops by 1/e and 1/e^2, showing high recombination probability even in the 80-120 keV hard X-ray region when UV lasers are used.

We also implemented a semi-classical study of the effects of the Lorentz force on electrons during high harmonic generation in the soft and hard X-ray regions driven by near- and mid-infrared lasers with wavelengths from 0.8 to 20 µm, and at intensities below 10^{15} W/cm^2. The transverse extent of the longitudinal Lorentz drift is compared for both Gaussian focus and waveguide geometries. Both geometries exhibit a longitudinal electric field component that cancels the magnetic Lorentz drift in some regions of the focus, once each full optical cycle. We show that the Lorentz force contributes a super-Gaussian scaling which acts in addition to the dominant high harmonic flux scaling of $\lambda^{-(5-6)}$ due to quantum diffusion. We predict that the high harmonic yield will be reduced for driving wavelengths > 6 μm, and that the presence of dynamic spatial mode asymmetries results in the generation of both even and odd harmonic orders. Remarkably, we show that under realistic conditions, the recollision process can be controlled and does not shut off completely even for wavelengths >10 μm and recollision energies greater than 15 keV.

Publications and Patents from ARO Support

1. D. Popmintchev, C. Hernández-García, F. Dollar, C. Mancuso, J. Pérez-Hernández, M.C. Chen, A. Hankla, X. Gao, B. Shim, A. Gaeta, M. Tarazkar, D. Romanov, R. Levis, J. Gaffney, M. Foord, S. Libby, A. Jaron-Becker, A. Becker, L. Plaja, M. Murnane, H. Kapteyn, T. Popmintchev, "Efficient soft X-ray high harmonic generation in multiply-ionized plasmas: the ultraviolet surprise," *Science* **350**,1225 (2015).

2. T. Popmintchev, D. Popmintchev, M. M. Murnane, and H. Kapteyn, "Generation of VUV, EUV, and X-ray Light Using VUV-UV-VIS Lasers," Patent US14477853 (2015).

3. Lorentz drift compensation in high harmonic generation in the soft and hard X-ray regions of the spectrum, B. Galloway, D. Popmintchev, M. Murnane, H. Kapteyn, T. Popmintchev, Optics Express **24**, 21818 (2016).

Recent Awards

2015 American Indian Science and Engineering Society Most Promising Scientist or Engineer Award (Franklin Dollar)
2016 IUPAP Young Scientist Award (Tenio Popmintchev)
2016 Honorary Degree of Doctor of Science, Uppsala University, Sweden (Margaret Murnane)
2015 Elected to Member, American Philosophical Society (Margaret Murnane)
2015 Honorary Degree of Doctor of Science, University College Dublin (Margaret Murnane)
2015 Honorary Degree of Doctor of Science, Trinity College Dublin (Margaret Murnane)
2014 Moore Foundation Experimental Investigator Award (Margaret Murnane)
2014 CU Boulder Inventor of the Year (shared between Henry Kapteyn and Margaret Murnane)
2013 Honorary Member, Royal Irish Academy (Margaret Murnane)