Quantum Electron Optics

770. WE-Heraeus-Seminar

27 – 30 June 2022

at the Nahsholim Seaside resort, Israel

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 770. WE-Heraeus-Seminar:

The controlled interaction of electron beams with matter enables a multitude of possibilities for either analytical characterization techniques such as cathodoluminescence or electron energy-loss spectroscopy, or advanced applications in acceleration science as well as fundamental quantum optical research. The stimulated processes made available by the so-called photon-induced near-field electron microscopy technique in contrast with the spontaneous processes are intensively studied by our community, allowing us to understand the intimate quantum processes of the nanoworld. Thus, topics such as coupling to quantum objects and decoherence are becoming more and more tractable and applicable. Our workshop aims at bringing together experts from both experiment and theory and from this field and related fields, including Smith Purcell radiation generation, electron beam shaping, ultrahigh brightness electron sources, strongfield physics and well-matching parts from the large field of nanophotonics. Our organization team as well reflects these diverse and at the same time complementary scientific approaches. Invited speakers include a well-balanced mixture spanning from world-leading senior experts to younger colleagues just starting their labs, from all over the world, including colleagues from Israel, Germany, Austria, Canada, France, Japan, the Netherlands, Spain, and the United States. We hope and are confident that experienced as well as young researchers will participate and enjoy flourishing discussions and interactions - in a beautiful setting at the Mediterranean Sea. The poster prize winners will be given the opportunity to present a hot topic talk.

Scientific Organizers:

Prof. Dr. Ady Arie	Tel Aviv University, Israel E-mail: ady@tauex.tau.ac.il
Prof. Dr. Peter Hommelhoff	Universität Erlangen, Germany E-mail: peter.hommelhoff@physik.uni-erlangen.de
Prof. Dr. Nahid Talebi	Universität zu Kiel, Germany E-mail: talebi@physik.uni-kiel.de

Introduction

Administrative Organization:

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Elisabeth Nowotka

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Internet: www.we-heraeus-stiftung.de

Venue:

Nahsholim Seaside Resort
at the foot of Mount Carmel
Israel

Phone +972-4-6399533

Program

Monday, 27 June 2022

	Bus transfer to the venue:	
08:30 am	First pickup point: *Hayarkon Street 287, Tel Aviv, near Tal Hotel*	
09:00 am	Second pickup point: *Gate no. 4, Tel Aviv University*	
10:00 – 10:30	**Registration for the seminar**	
10:30	Scientific organizers	**Welcome words**
10:40	Jürgen Mlynek	**Welcome words**
11:00	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
11:15 – 12:00	Nahid Talebi	**Phase-locked photon-electron spectroscopy**
12:00 – 12:20	Osip Schwartz	**Controlling electrons with CW lasers**
12:30	*LUNCH*	

Program

Monday, 27 June 2022

14:00 – 14:45	Wolfgang Schleich	**Quantum electron optics and analogies to atom optics**
14:45 – 15:30	Claus Ropers	**Interfacing photonics with electron microscopy**
15:30 – 16:30	*COFFEE BREAK and ROOM CHECK-IN*	
16:30 – 17:15	Javier Garcia de Abajo	**Quantum aspects of the interaction between free electrons, light, and photonic nanostructures**
17:15 – 17:35	Catherine Kealhofer	**Nanotip sources for time-resolved electron diffraction**
17:35 – 17:55	Iva Brezinova	**Exchange-mediated mutual correlations and dephasing in free-electron and light interactions**
18:00 – 19:00	Discussion time	
19:00	*DINNER*	

Program

Tuesday, 28 June 2022

06:30 – 07:00	*Beach run/walk*	
07:30	*BREAKFAST*	
08:30 – 09:15	Ido Kaminer	**Quantum optics with free electrons**
09:15 – 09:35	Andrea Konečná	**Entangling free electrons and optical excitations**
09:35 – 09:55	Valerio Di Giulio	**Quantum optics and electron beams**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:15	Roy Shiloh	**Nanophotonic on-chip acceleration of free electrons**
11:15 – 11:35	Sophie Meuret	**Ultrafast electron microscopy with a parabolic mirror: Cathodoluminescence and PINEEM**
11:35 – 11:55	Yiming Pan	**PINEM synthetic dimensions using ultrafast free electrons**
11:55 – 12:00	Group photo	
12:30	*LUNCH*	

Program

Tuesday, 28 June 2022

13:30 – 15:00	**Poster flashes**	
15:00 – 15:30	*COFFEE BREAK*	
15:30 – 16:15	Rafal Dunin-Borkowski	**Opportunities for studies of electron-light-matter interactions in the transmission electron microscope**
16:15 – 17:00	Jacob Scheuer	**Enhanced light-electron interactions via plasmonic metasurfaces**
17:00 – 19:00	**Visit Tel Dor and Glazier Museum**	
19:00	*DINNER*	
20:00	**Poster session** with beer and wine	

Program

Wednesday, 29 June 2022

06:30 – 07:00	*Beach run/walk*	
07:30	*BREAKFAST*	
08:30 – 08:45	**Poster prize announcement**	
08:45 – 09:30	Mathieu Kociak	**Deciphering the fate of optical excitations with photons and electrons**
09:30 – 10:15	Avraham Gover	**Quantum electron-optics**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:30	Nirit Dudovich	**Attosecond interferometry**
11:30 – 11:50	Aviv Karnieli	**Quantum sensing of strongly coupled light-matter systems using free electrons**
11:50 – 12:10	Yonatan Israel	**Multi-pass and quantum limits to electron microscopy**
12:30	*LUNCH*	
14:00 – 14:45	Ebrahim Karimi	**Structured quantum waves: Concepts and applications.**
14:45 – 17:00	**Discussion time**	
18:00	*Bus transfer to a restaurant Caesarea*	
	HERAEUS DINNER in Caesarea Port	
	followed by a night tour in Caesarea	

Program

Thursday, 20 June 2022

06:30 – 07:00	*Beach run/walk*	
07:30	*BREAKFAST*	
08:30 – 09:15	Martin Kozák	**Optical ponderomotive control of free electrons – from inelastic scattering to quantum coherent interactions**
09:15 – 10:00	Peter Baum	**Attosecond electron microscopy and free-electron qubits**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 10:50	Freyja Ullinger	**The logarithmic phase singularity in the inverted harmonic oscillator**
10:50 – 11:10	Marius Constantin Chirita Mihaila	**Electron beam shaping with light**
11:10 – 11:20	**Poster prize winner talk**	
11:20 – 11:30	**Poster prize winner talk**	
11:30 – 11:40	**Poster prize winner talk**	
12:30	*LUNCH*	
	End of the seminar and departure	
14:00	***Bus transfer to Tel Aviv***	

Dinner will not be served on Thursday

Posters

Posters

Salma Abo Toame	**Simulating the probing of plasmonic fields in space and time using slow-electron holography**
Yuval Adiv	**Observation of 2D Cherenkov radiation and its quantized photonic nature**
Hadar Aharon	**Quantum-classical transition exhibited in micro sphere optical modes exited by relativistic electrons**
Avi Auslender	**Measuring the mean inner potential of Bernal graphite using off-axis electron holography**
Zahava Barkay	**Quantitative CL in SEM for characterization of high TC superconductors**
Maximilian Johannes Black	**Investigation of plasmonic bloch modes by complementary cathodoluminescence and optical dark-field spectroscopy measurements**
Simona Borrelli Jom Luiten	**Pulsed-laser phase plate for UEM: Theoretical feasibility**
Raphael Dahan	**Creation of photonic cat and GKP States using shaped free electrons**
Dominik Ehberger	**Electron pulse compression with terahertz electromagnetic fields**
Avraham Eitan	**An ultrafast source of attosecond electron pulses triggered by a surface plasmon**
Maor Eldar	**Slow-electron PINEM and its anomalous Wannier-Stark localization in synthetic space**
Aharon Friedman	**Numerical simulation of multi PINEM electrons in free electron bound electron resonant interaction**

Posters

Lucas Grandits	**Theory of ponderomotive transverse electron beam shaping**
Urs Haeusler	**Imaging the field inside dielectric laser acceleration nanostructures**
Germann Hergert	**Photon-induced near-field interaction in ultrafast low energy electron microscopy**
Stefan Kempers	**Pulsed laser phase plate for UEM: Experimental realization**
Matthias Kolb	**Towards driving quantum systems with the non-radiating near-field of a modulated electron beam**
Stewart Koppell	**Applications in electron microscopy for electron-photon correlations**
Michael Krueger	**Sub-optical-cycle electron pulse trains from metal nanotips**
Yonas Lebsir	**Cathodo- and photoluminescence characterization of single photon emitters**
Joshua Reynolds	**Nanosecond electron pulse production via Schottky-enhanced photoemission**
Dolev Roitman	**Shaping of electron beams using sculpted thin films**
Georgi Gary Rozenman	**Observations of Bohm trajectories in surface gravity water waves**
Franz Schmidt-Kaler	**Chip-based electrostatic Paul trap-like structures for electron beam manipulation**
John Simonaitis	**Coherent interactions between electrons and photons in a 10 KeV scanning electron microscope**

Posters

Yonatan Sivan	**Non-equilibrium theory of electron emission from metals**
Shai Tsesses	**Tunable photon-induced spatial modulation of free electron wavepackets**
Ofir Yesharim	**Generating spatially entangled qubits using quantum nonlinear holography**
Bin Zhang	**Quantum electron wavepacket interaction with light and matter**
Matthias Zimmermann	**Interferometry viewed from phase space**
Robert Zimmermann	**"On-chip" ponderomotive optics for quantum electron microscopy**

Abstracts of Talks

(in alphabetical order)

Attosecond Electron Microscopy and Free-Electron Qubits

Peter Baum

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The fundamental reason behind almost any light-matter interaction are atomic and electronic motion in space and time. In order to provide a movie-like access to such dynamics, we unify electron microscopy with attosecond laser technology. In this way, we combine the awesome spatial resolution of modern electron beams with the spectacular time resolution that is offered by the cycle period of light [1]. Selected results will be reported on the electric fields within metamaterials [2-3], the Einstein-de-Haas effect on atomic dimensions [4], the reaction path of phase transitions [5] and the formation of free-electron qubit states [6]. Many breakthroughs in science and technology have been achieved by disruptive imaging techniques, and our 4D electron microscopy may play this role for light-matter interaction on atomic dimensions.

References

[1] C. Kealhofer, W. Schneider, D. Ehberger, A. Ryabov, F. Krausz, P. Baum, “All-optical control and metrology of electron pulses”, Science 352, 429 (2016).

[2] A. Ryabov and P. Baum, “Electron microscopy of electromagnetic waveforms”, Science 353, 374 (2016).

[3] K. J. Mohler, D. Ehberger, I. Gronwald, C. Lange, R. Huber, P. Baum, „Ultrafast electron diffraction from nanophotonic waveforms via dynamical Aharonov-Bohm phases“, Science Advances (2020).

[4] S. R. Tauchert, M. Volkov, D. Ehberger, D. Kazenwadel, M. Evers, H. Lange, A. Donges, A. Book, W. Kreuzpaintner, U. Nowak, P. Baum, “Polarized phonons carry angular momentum in femtosecond demagnetization”, Nature 602, 73 (2022).

[5] P. Baum, Ding-Shyue Yang, A. H. Zewail, “4D Visualization of Transitional Structures in Phase Transformations by Electron Diffraction”, Science 318, 788 (2007).

[6] M. Tsarev, A. Ryabov, P. Baum, “Free-Electron Qubits and Maximum-Contrast Attosecond Pulses via Temporal Talbot Revivals”, Phys. Rev. Res. 3, 043033 (2021).

Exchange-Mediated Mutual Correlations and Dephasing in Free-Electron and Light Interactions

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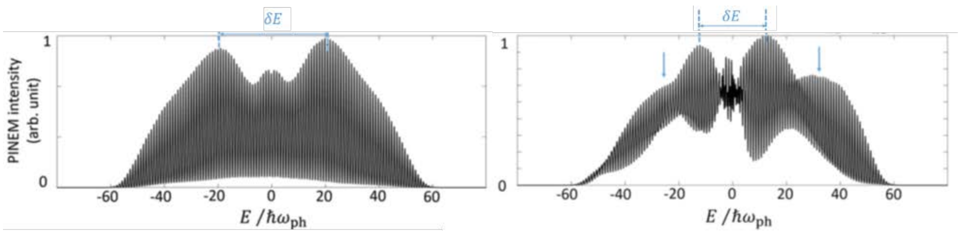
[2] Institute for Theoretical Physics, Vienna University of Technology, Wiedner Hauptstrasse 8-10/136, Vienna, Austria

Most of the concepts in electron microscopy have exploited quantum features of electrons on a single particle level so far. Coherent scattering of individual electrons on a probe and the interference of paths with different phase shifts allows retrieving information about a probe. Coherent scattering of electrons on light allows ultrafast control and shaping of electron wave packets [1,2,3] that can be used in advanced microscopic setups. The quantum world, however, bears further fascinating effects when more than one particle is involved, entanglement being a prominent example. In this theoretical study, we design and numerically explore a thought experiment to analyze the potential of using entanglement within electron microscopy. Within the setup of near-field electron microscopy (PINEM) [4] we investigate whether information can be transferred between two spin-correlated electrons. We find marked differences between spin-polarized and spin-unpolarized electron pairs and show that transfer of quantum phase information is possible only in the first case [5]. This transfer is mediated by the exchange correlation between the electrons while dephasing is dominated by the Coulomb mean-field. Our findings might facilitate fermionic matter wave interferometry experiments designed to retrieve information about non-classical correlations and the mechanism of decoherence in open quantum system.



PINEM spectrum retrieved from spin-unpolarized (left) as compared to spin-polarized (right) electron pairs. The electrons interact with a laser induced plasmonic excitation of a gold nanoparticle.

References

[1] A. Feist et al., Nature **521**, 200–3 (2015)
[2] N. Talebi, and C. Lienau, New J. Phys. **21**, 093016 (2019)
[3] M. Kozák et al., Nat. Phys. **14**, 121–5 (2018)
[4] S. T. Park, M. Lin, and A. H. Zewail, New J. Phys. **12**, 123028 (2010)
[5] N. Talebi and I. Březinová, New J. Phys. **23**, 063066 (2021)

Electron beam shaping with light

M. C. C. Mihaila[1,2,3], P. Weber[1,2], M. Schneller[1,2], L. Grandits[1,2], S. Nimmrichter[4], and T.Juffmann[1,2]

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Introduction

Nanoscale spectroscopy and attosecond coherent control of the electron wave function can be realized by shaping the electron wave-packets with light fields in the vicinity of matter [1]. Still, these methods can suffer from inelastic scattering or beam induced deterioration. Pondemorotive interactions with electrons in free space avoid these problems [2,3,4,5]. Here, we demonstrate programmable electron beam shaping using an intense laser beam modulated by a spatial light modulator (SLM) [6].

Methods

A Scanning electron microscope (SEM) was modified to allow operation in transmission mode and to enable laser triggered electron emission from a Schottky Electron Gun. In the specimen chamber, the electron beam interacts with a shaped counter-propagating laser pulse, inducing local phase shifts to the electron wave function. For shaping the laser, we calculate the required phase patterns that are displayed on the SLM by using a modified Gerchberg-Saxton algorithm. Spatial and temporal overlap between the electrons and laser pulses is achieved without an energy filter.

Results

We show programmable electron deflection patterns and both concave/convex electron lenses having a few millimeter focal lengths, like those in state-of-the-art magnetic lenses.

References

[1] O. Reinhard, I. Kaminer, ACS Photonics 7, 2859 (2020).
[2] D. L. Freimund et al, Nature 413, 142 (2001).
[3] M. Kozak et al, Nat physics 14, 121 (2018).
[4] Schwartz et al, Nat Methods 16, 1016-1020 (2019).
[5] FJG de Abajo, A. Konecna, PRL 126.12 (2021): 123901.
[6] https://arxiv.org/abs/2203.07925.

Quantum optics and electron beams

V. Di Giulio[1] and F. Javier García de Abajo[1,2]

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Electrons in electron microscopes offer the possibility to measure material properties with nanometer resolution in several fashions depending on the signal analyzed. In particular, electron energy loss spectroscopy (EELS) can be considered the richest source of information as it carries the influence from the surface-sustained modes as well as from the bulk response of the system. In the last two decades, the synchronization of ft laser illumination with electron pulses at the sample allows to study the ultrafast dynamics of nanostructured materials and their influence on optical near-fields. The evanescent nature of the field produced by the excitations efficiently overcomes the usual energy-momentum mismatch preventing free photons and free electrons to interact. Here, under strong laser amplitudes (~10^8 V/m) the electron interacts with a highly populated coherent state exchanging several light quanta and reshaping its electron wave function. This effect, named PINEM [1], was later exploited to longitudinally and transversally modulate the electron wave function. Such possibility prompted a cascade of further theoretical studies aimed to explore the effects of the interaction between such shaped electrons and a secondary sample [2,3,4], in particular trying to answer the question: “which state of light would a shaped electron produce in the interaction with a cavity?”.

In this work, we use macroscopic quantum electrodynamics to describe the quantum nature of the interaction between an evanescent optical field and a fast electron trying to answer to the aforementioned question. In addition, we analyze the possibility of directly creating coherent squeezed states in bosonic cavity-supported modes.

References

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[3] O. Kfir, V. Di Giulio, F. Javier García de Abajo and C. Ropers, *Sci. Adv.,* **7**, (2021).
[4] V. Di Giulio, O. Kfir, C. Ropers and F. Javier García de Abajo, *ACS Nano*, **15**, (2021).

Attosecond Interferometry

N. Dudovich[1]

[1]Weizmann Institute of Science, Rehovot, Israel

Attosecond science is a young field of research that has rapidly evolved over the past decade. One of the most important aspect of attosecond spectroscopy lies in its coherent nature. Resolving the internal coherence is a primary challenge in this field, serving as a key step in our ability to reconstruct the internal dynamics. As in many other branches in physics, coherence is resolved via interferometry. In this talk, I will describe advanced schemes for attosecond interferometry. The application of these schemes provides direct insights into a range of fundamental phenomena in nature, from tunneling and photoionization in atomic systems to ultrafast chiral phenomena and attosecond scale currents in solids.

Opportunities for studies of electron-light-matter interactions in the transmission electron microscope

Amir H. Tavabi[1], Vincenzo Grillo[2], Giovanni Maria Vanacore[3], Giulio Pozzi[1,4], Rafal E. Dunin-Borkowski[1]

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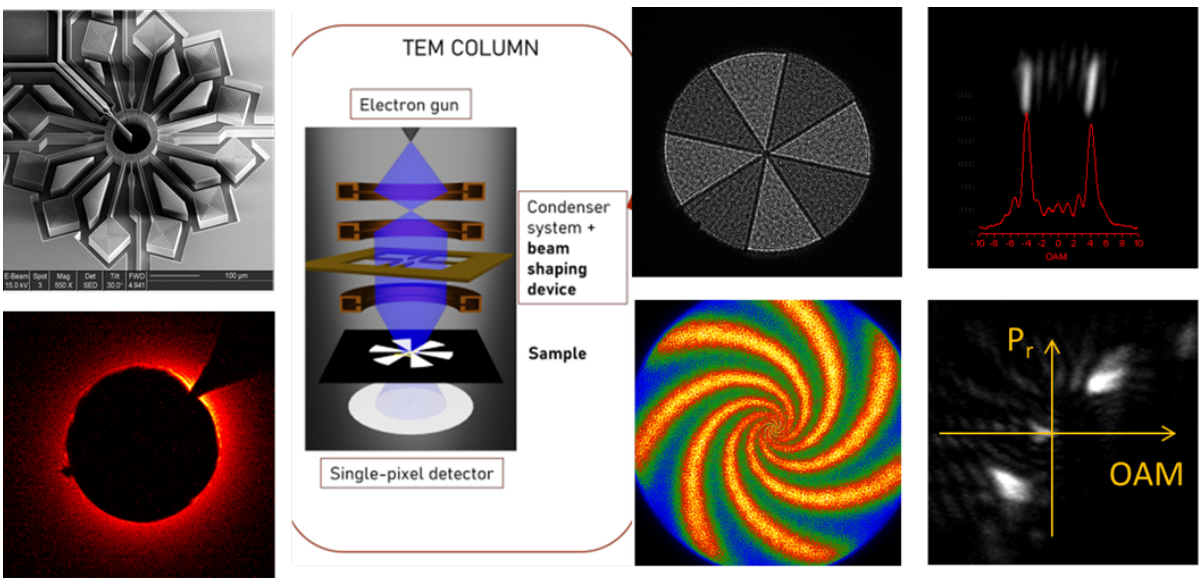
The transmission electron microscope is an ideal instrument for probing fundamental aspects of quantum mechanics. This talk will start from several variations of the double slit experiment and from the development of a Marton interfereometer to realize an Elitzur-Weidmann bomb testing interferometer. It will then describe the orbital angular momentum (OAM) sorter, a device that optimizes single electron quantum state measurements and offers an ideal basis for decoherence studies in inelastic scattering involving the excitation of collective modes. The final theme will be electron-environment correlations that are at the basis of computational and "real" ghost imaging. A theoretical framework will be presented based on photonic electron light modulation and on the use of MEMS-based programable phase plates (MbPPPs). The talk will conclude with prospects for innovative instrumentation development. Enzo Rotunno, Paolo Rosi, Stefano Frabboni, Alberto Roncaglia, Penghan Lu and other colleagues are thanked for valuable contributions to this work.



Left to right: Tunable electrostatic vortex generator and largest achieved 1st order electron vortex beam; Setup for ghost imaging using MbPPPs; OAM-dispersed spectrum for a +-4 petal beam and a chiral vortex L=7 beam.

Quantum Aspects of the Interaction between Free Electrons, Light, and Photonic Nanostructures

F. Javier García de Abajo[1,2]

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[2] ICREA-Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain

Electron beams offer a unique additial element in the quantum photonic Lego. The control over the longitudinal and transverse properties of electron beams has recently experienced an impressive boost because of the combination of new advances in electron microscope instrumentation, in particular with the use of ultrafast light pulses, and the ability to synthesize femtosecond electron wave packets. In this talk, we will overview key concepts describing the associated interactions between free electrons, light, and photonic nanostructures, making emphasis on quantum aspects and exploring several exciting challenges and emerging opportunities. We will further discuss potential applications in noninvasive spectroscopy and microscopy, the possibility of sampling the nonlinear optical response at the nanoscale, the manipulation of the density matrices associated with free electrons and optical modes in a specimen, optical modulation of electron beams, and improved schemes for electron-driven light emission over a wide range of photon energies.

Quantum Electron-Optics

***Avi Gover*[1], , *Du Ran*[1,2], *Bin Zhang*[1], *Yi-Ming Pan*[3], *Reuven Ianconescu*[1,4], *Jacob Scheuer*[1], *Aharon Friedman*[5], *Ammon Yariv*[6]**

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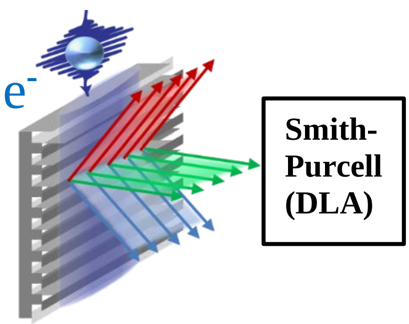
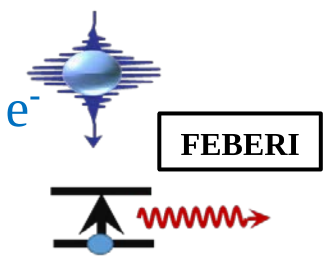
Abstract. "Quantum Electron Optics" is an emerging area owing its parentage to the fields of electron optics and quantum optics. This area comprises interaction schemes that can be presented in the quantum or classical limit, such as Compton (Thompson) Scattering, Kapitza-Dirac effect, Free Electron Laser (FEL), Dielectric Laser Accelerator (DLA), and entirely quantum effects as Photo-Induced Near-field Electron Microscopy (PINEM) and ghost imaging (quantum microscope).

Our approach to the field is based on presentation of the electron as a Quantum Electron Wavepacket (QEW). This reveals the reality of the wavefunction in stimulated interaction with light and in spontaneous superradiance, and delineates the quantum to classical transition limits.

Further application of the model to quantum electron interaction with matter, brought about the new concept of Free-Electron Bound-Electron Resonant Interaction (FEBERI) and its possible use for interrogating the quantum state (qubits and super-qubits) of Two-Level Systems. We also will present preliminary computation results of FEBERI Rabi oscillation with multiple modulation-correlated QEWs.



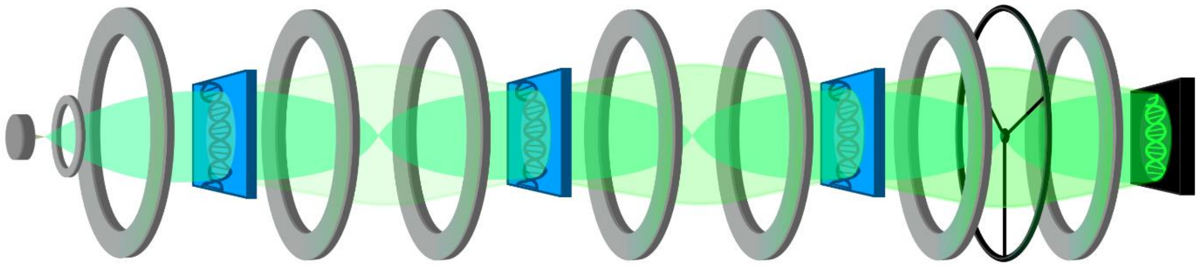


Multi-pass and quantum limits to electron microscopy

Y. Israel[1]

[1]*Physics Department, Stanford University*

While modern transmission electron microscopes are capable of imaging at atomic resolution, this has not yet been possible for many delicate samples, such as single molecules, that are degraded by high energy electrons. A multi-pass approach has been proposed as a viable route to enhancing the dose-efficiency in transmission electron microscopy [1]. In this talk, I will present quantum limits to phase contrast electron microscopy [2] as well as electron energy loss spectroscopy (EELS), showing that multi-passing is nearly quantum optimal. I will also discuss the efforts of our group at Stanford to building the first proof-of-concept multi-pass transmission electron microscope at 10 keV [3-5].



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Quantum Optics with Free Electrons

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Until recently, work in quantum optics focused on light interacting with bound-electron systems such as atoms, quantum dots, and nonlinear optical crystals. In contrast, free-electron systems enable fundamentally different physical phenomena, as their energy distribution is continuous and not discrete, allowing for tunable transitions and selection rules. We have developed a platform for studying free-electron quantum optics at the nanoscale. We demonstrated it by observing the first coherent interaction of a free electron with a photonic cavity and first interaction with the quantum statistics of photons. These capabilities open new paths toward using free electrons as carriers of quantum information and for measurement of quantum coherence of individual quantum systems.

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Quantum sensing of strongly coupled light-matter systems using free electrons

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Strongly-coupled light-matter systems[1] have been a staple of cavity quantum electrodynamics and are key elements in quantum technologies. Especially in the optical range, full control of highly-connected multi-qubit systems necessitates high spatial resolution probes, which are currently inaccessible. Inspired by the recent surge of interest in the quantum interactions between free-electrons and photons[2–5] and with material emitters[6–11], here we propose the use of free electrons as high-resolution quantum sensors for strongly-coupled light-matter systems. We demonstrate theoretically how quantum interference in the electron energy spectrum gives rise to a quantum-enhanced sensing protocol for the position and polarization of a sub-nm emitter inside a cavity. We further establish that shaped free-electron wavepackets can be utilized to measure the polaritonic quantum state of the hybrid light-matter system. Our results showcase the great versatility and applicability of quantum interactions between free-electrons and strongly-coupled cavities, relying on unique properties of free-electrons as strongly interacting flying qubits with miniscule dimensions.

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Nanotip sources for time-resolved electron diffraction

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Laser-induced electron emission from tungsten nanotips has been used to generate short electron pulses for time-resolved electron diffraction. Nanotips have small effective source sizes and therefore low intrinsic emittance. Moreover, they can be operated with high surface electric fields, which can mitigate temporal broadening of the pulse. I will discuss advantages and disadvantages of some possible tip materials beyond tungsten, including materials that might be used as spin-polarized electron sources.

Deciphering the fate of optical excitations with photons and electrons

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The wealth of information gained by electron spectroscopies, such as EELS, CL, PINEM or EEGS, on the physical or material properties of nanobjects could no longer be disputed [1].
However, the correlative use of the different spectroscopies is still in its infancy. Since the different techniques give access to different physical phenomena (absorption, scattering, luminescence, …), it is expected that correlating them could answer precise questions such as: “how radiative is an optical mode?” or “which part of the absorption band is responsible for the different luminescence lines of a semiconductor?”
In this talk, we will first introduce correlative EELS, CL and EEGS spectroscopy in a highly monochromated machine. The high spectral resolution of both techniques will make clear how the difference in coupling of plasmons to electrons and photons affects the resonance as seen in EELS and EEGS. Despite the very high monochromaticity of the beam (~30 meV at 200 keV), we will show that EEGS can be several orders of magnitude better resolved than EELS [3], much along the lines of the work of ref. [4], but here demonstrated on arbitrary photonic samples.
In the case of 2D semiconducting structures, we will see how the conjunction of sub-10 meV EELS and high efficiency CL permits to demonstrate a direct analogy between macroscopic optical absorption and luminescence on the one hand side, and EELS and CL on 2D semiconducting materials on the other side [2]. Striking differences, such as the direct observation of trions in CL but not in EELS will be emphasized. Nevertheless, the physical origin of such differences is still to be understood.
Therefore, beyond correlation, we will show that *coincidence* between an absorption event at a given energy (as revealed by EELS) and an emission event at potentially another energy (as revealed by CL) can shine light on the different pathways from absorption to emission, eventually revealing the fate of an optical excitation [5].

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Entangling free electrons and optical excitations

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Quantum entanglement is of vital interest in quantum computing and cryptography, for which there is currently an intense search for practical physical realizations [1,2]. Here, we suggest that the inelastic interaction of shaped electron beams with samples featuring low-energy excitations, such as localized surface plasmons in metallic nanoparticles or molecular vibrations in atomic-scale structures, can yield entanglement between final energy-filtered electron states and modes excited in the sample. We demonstrate that by tailoring the electron wave function of a fast electron (e.g., using tunable electron phase plates [3-5]) we can achieve control over the resulting entangled states [6].
Besides the generation of entanglement, our scheme can be exploited for triggered selection of mode excitation based on both pre-shaping of the electron wave function and final state post-selection at the detector. This technique could indeed be used to probe the dynamics of a specific targeted mode via an additional external probe synchronized with the incident electrons. Importantly, this approach would enable to discern even degenerate modes that would emerge undistinguishable within a common energy feature without the kind of pre- and post-selection that we envision here.

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Optical ponderomotive control of free electrons – from inelastic scattering to quantum coherent interactions

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This contribution is focused on the review of recent advances in the field of the interaction of free electron beams with the ponderomotive potential of optical fields. Classical and quantum coherent regimes of the interaction will be discussed along with their potential applications in advanced electron microscopy and associated techniques. In particular I will focus on the theoretical description of the strong inelastic interaction beyond the nonrecoil approximation and the description of the asynchronous regime of the interaction, which allows to selectively accelerate or decelerate the electrons while generating a narrow momentum distribution.

Ultrafast electron microscopy with a parabolic mirror: Cathodoluminescence and PINEM

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In this presentation, we will discuss how the use of a parabolic mirror in an ultrafast transmission electron microscope allows for the most efficient collection and injection of light. We'll look at how it affects photon-induced near-field electron microscopy (PINEM) and enables time-resolved cathodoluminescence (TRCL)[1]. PINEM was first introduced and developed by Zewail's group[2–4]. It uses the overlap in space and time of a femtosecond electron pulse with an intense laser pulse. In a stroboscopic fashion, the electron pulse maps at the nanoscale the near field created by the laser pulse. PINEM is applied for example to probe plasmonic modes[5,6] and to shape the electron wave function[7,8]. We will see how the parabolic mirror impact the induced near-field while reducing dramatically the laser spot.

Time-resolved Cathodoluminescence in a scanning electron microscope enabled the measurement of the lifetime of excited states in semiconductors with a sub-wavelength spatial resolution[9,10]. While all these pioneering studies were done using a scanning electron microscope, the improvement of the spatial resolution and the combination with other electron-based spectroscopies offered by transmission electron microscopes will be a step forward for TR-CL. In this presentation, we will discuss the first time-resolved cathodoluminescence experiments within a transmission electron microscope.

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PINEM synthetic dimensions using ultrafast free electrons

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We proposed a synthetic dimension for ultrafast free electrons based on the discrete energy sidebands in photon-induced near-field electron microscopy (PINEM) [1-3]. The PINEM synthetic dimension can offer a powerful way to coherently shape or modulate free-electron wavefunction in systems such as ultrafast transmission electron microscopy, dielectric laser accelerator, and quantum free-electron laser. Here, we present an example of a paradigm - synthetic Bloch oscillation [5]- by constructing an effective constant force along the energy axis to demonstrate the control of PINEM electrons. The setup and results are presented in Fig.1. Also, we achieve the diffraction management of PINEM electrons and demonstrate the capability of mimicking linear optics with free electrons, such as diffraction management, negative refraction, discrete Talbot effects in the synthetic space. Our findings show that ultrafast free-electron synthetic dimensions can serve as a novel quantum simulation platform (unlike simulations using atoms [2] or photons [3]) to investigate a wide range of phenomena such as artificial gauge fields, topological phases, and solid-state physics.

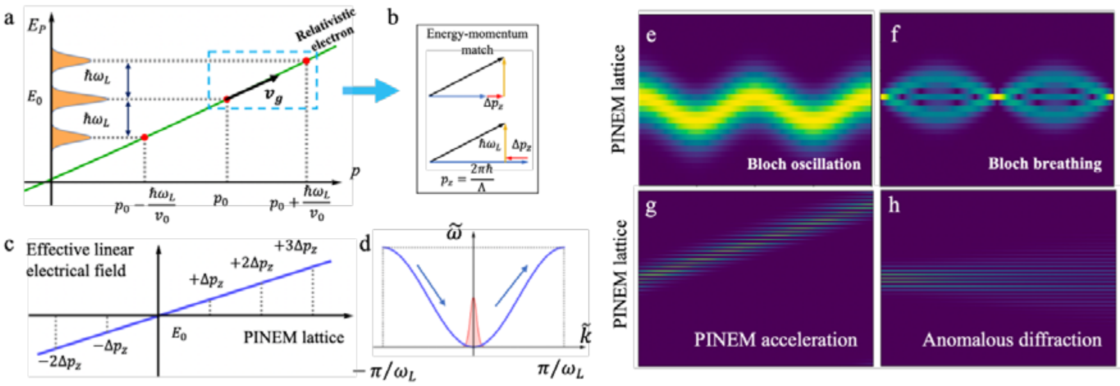

Fig. 1: Schematic diagram of PINEM synthetic dimension using ultrafast free electrons and typical spectral patterns in PINEM lattice. (a) PINEM sidebands develop when the electron experiences the laser-induced phase modulation on a grating. (b) A detuning between the grating period and the laser frequency results in an effective constant force. (c) The sidebands act as a synthetic lattice. (d) The synthetic dispersion represents electron hopping between PINEM lattices. (e, f) The PINEM electron exhibits Bloch oscillation for the multiple sidebands within a Gaussian envelop and Bloch breathing for single sideband input. (g, h) The spectral evolutions of PINEM electrons undergoing particle acceleration, and anomalous diffraction, respectively.

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Interfacing photonics with electron microscopy

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Providing the most detailed views of atomic-scale structure and composition, Transmission Electron Microscopy (TEM) serves as an indispensable tool for structural biology and materials science. Optical excitations in electron microscopy are accessible through spontaneous inelastic scattering of electrons, analysed in electron-energy loss and cathodoluminescence spectroscopy. The stimulated variants of the underlying scattering processes become accessible through optical illumination of the sample.

This talk will discuss recent work harnessing inelastic electron-light scattering in imaging, spectroscopy and for the advancement of free-electron quantum optics. Specific examples include the imaging of near-field intensity distributions [1] and Lorentz microscopy of optical fields [2], as well as the coherent control of the free-electron quantum state for spatial [3] and temporal [4-6] electron beam manipulation.

Moreover, recent progress in the coupling of electron beams to whispering gallery modes [7] and integrated photonic resonators [8] will be discussed, including the preparation and characterization of electron-photon pair states [9].

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Enhanced light-electron interactions via plasmonic metasurfaces

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Manipulating and controlling the properties of free electrons by light is attracting much attention as this approach facilitates new studies and applications in both the classic and quantum regimes. Enhancing such interactions requires the generation of intense and often highly localized fields. An attractive approach for generating such intense fields is by illuminating a surface which is patterned by sub-wavelength nanostructures. Theses nanostructures could be metallic (plasmonic) or dielectric, where each type has its own advantages and drawbacks. Plasmonic structures exhibit Ohmic losses at optical frequencies but are simpler to fabricate, particularly in deep sub-wavelength dimensions, thus offering a new paradigm for manipulation of particle beams adjacent to the surface.
In this talk we will present plasmonic metasurfaces as an attractive platform for electron-beam manipulation, particularly for acceleration of sub-relativistic particles as well as a potential tunable source based on Cherenkov-Smith-Purcell radiation. Compared to the more established dielectric laser accelerators, the metasurface laser accelerators exhibit lower net acceleration gradient but improved efficiency and simpler realization, rendering them attractive for applications where lower power and compact dimensions are important.

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Quantum electron optics and analogies to atom optics

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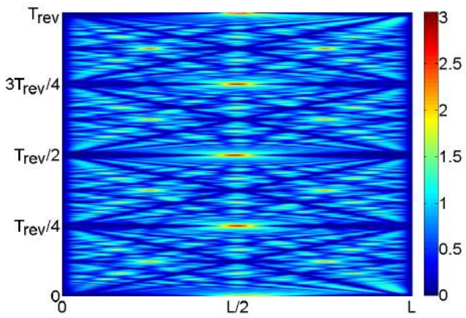
The emerging field of quantum electron optics shares many inspiring analogies with atom optics in quantized light field [1]. Indeed, in both branches of quantum optics the center-of-mass motion as well as the light field are treated quantum mechanically. Even a coupling to the internal state exists in both topics.

In this talk we illuminate these common properties using three examples: (i) the measurement of the photon statistics [2] by the deflection of atoms, (ii) the observation of decoherence [3] by quantum carpets [4], and (iii) the physics of the quantum free-electron laser [5].



Quantum carpet in the absence of decoherence

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Controlling electrons with CW lasers

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Ponderomotive interaction of electron waves with lasers offers a path towards powerful and versatile control of electron wave functions in space and time. We are building a new experimental platform at WIS, based on a transmission electron microscope (TEM). The experiments will be based on continuous-wave (CW) lasers, using high-finesse focusing resonators[1] to reach a laser intensity in the TW/cm^2 range.
Free-space electron interactions with CW laser beams enable gentle manipulation of highly coherent electron waves in a well-controlled environment, preserving the capability of a conventional high-end TEM for generation of tightly focused electron beams and Angstrom-resolution imaging. The resonator-enhanced laser wave can serve as a coherent lossless beam-splitter, a phase modulator, a diffraction grating or a tunable deflector. A time-dependent laser field (e.g., comprising two monochromatic waves) can be used to temporally modulate electron beam, generate ultrashort pulses, or deterministically accelerate electron waves.
As the first experimental goal, we will use these capabilities to create a Zernike phase plate for TEM that both phase-shifts and optically attenuates the unscattered wave, to balance the local oscillator amplitude with the scattered wave for optimal contrast. We will also explore extinguishing the unscattered wave entirely to achieve dark-field TEM imaging.
CW lasers control in a continuous-beam TEM also opens the door to the generation of tightly focused, high average current temporally modulated electron beams and ultrafast electron pulses for coherent control of quantum systems on the nanoscale[2], as well as for studies of radiation from temporally and spatially shaped electron waves.

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Nanophotonic on-chip acceleration of free electrons

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To satisfy energy and momentum conservation, a nanophotonic structure can act as a mediator in the interaction between photons and free electrons. This concept is the main driver behind many light-matter interaction phenomena including, among others, dielectric laser acceleration (DLA) and photon-induced near-field electron microscopy (PINEM). While the former can be treated classically using traditional accelerator physics models and approaches, the latter requires solving the Schrödinger equation and taking into account the wave nature of the electron wavepacket. The potential of accelerating electrons on a chip with gradients 1-2 orders of magnitude larger than traditional RF accelerator schemes defined DLA research as a novel, complementary technology with outstanding prospects. For example, DLAs promise table-top compact sources of high-energy electrons, which could be used for tunable radiation generation and medical treatments. We have already demonstrated electron beam transport on a nanophotonic chip, using the alternating phase focusing technique [1,2], and record 280 as electron bunch trains [3], for example. However, with only slight changes to the apparatus' parameters and a high-resolution magnetic electron energy-loss spectrometer, we can also demonstrate quantum photon-electron interaction such as PINEM, which manifests as a comb in the single electron wavepacket's energy spectrum, with the comb peaks separated by the interacting photon-energy [4]. In this talk, I will review the fundamentals of DLA, and outline the recent progress we made towards significant energy gains on nanophotonic chips, as part of the Accelerator On a Chip International Program (ACHIP).

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Phase-Locked Photon-Electron Spectroscopy

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Mechanisms of radiation from electron beams are routinely tailored in gigantic infrastructures such as free-electron lasers to perform coherent spectroscopy of materials excitations. However, even nano and mesoscale structures could provide sufficient tailoring mechanisms in interaction with electrons, to be applied to spectroscopy techniques [1-3]. Here, we provide the first proof-of-concept experiment highlighting the coherent mechanisms involved in phase-locked photon-electron spectroscopy of quantum materials and their dynamics. In our approach, precisely engineered electron-driven photon sources (EDPHSs) are used as photon clocks. The radiation from the EDPHS excites the sample at a delay (τ) with respect to the electron beam, that is controlled by changing the distance between the sample and the EDPHS. In addition, this technique allows us to directly map the decoherence mechanism by investigating the visibility of the spatial and spectral interference fringes. Using WSe_2 thin films as samples, we will specify the formation of exciton polaritons due to the self-hybridization effect and the associated spatial coherence as captured by electron-beam spectroscopy [4,5]. Phased-locked photon-electron spectroscopy when applied to WSe_2 flakes, allows us to unravel the photon-mediated spectral correlations between A and B excitons.

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The logarithmic phase singularity in the inverted harmonic oscillator

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Phenomena in quantum field theory, such as Hawking radiation [1] or acceleration radiation [2], or based on a logarithmic phase singularity at an event horizon in spacetime.
In this talk, we show that related effects emerge in the elementary quantum system of a one-dimensional inverted harmonic oscillator. In fact, the Wigner function corresponding to an energy eigenfunction of this system [3,4] clearly displays a horizon in phase space. Although usually hidden, even a logarithmic phase singularity in combination with an amplitude singularity appears after a suitable coordinate transformation.
Our insights [5] into this simple quantum system lay the foundation for future applications in the field of matter wave optics.

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Abstracts of Posters

(in alphabetical order)

Simulating the probing of plasmonic fields in space and time using slow-electron holography

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Low-energy electron holography (LEEH) is a technique at which coherent beams of electrons of low energy (< 500eV) are being produced by a point-like source, and irradiate a nearby sample [1]. A holographic point-projection image of the sample with a magnification of up to 10^6 is formed, which can be recorded on a distant screen. Low-energy electrons are more sensitive to plasmonic fields than ones of high energy. This means that the LEEH technique has an advantage over other techniques that rely on fast electrons, such as in transmission-electron-microscopy [2], particularly in investigating plasmonic features. In our study we developed a simulation in order to investigate the time and space behavior of emitted electron pulses from the moment they were emitted until reaching the screen and forming a holographic image, going through an interaction with a plasmonic nanostructure in the middle. Our simulation is a semi-classical one in which a numerical solution of the time-dependent Schrodinger equation (TDSE) and a classical trajectory model were presented [3]. The interaction with the plasmonic surface charges of the nanostructure was simulated using the boundary element method and holography algorithms [4,5]. The next step in our work will be to use the simulation's predictions in order to build an experimental setup and compare the experimental results with our predictions. We believe this study will not only have the potential to reveal new effects in plasmonics, but also to enable us to manipulate electron wavepackets in space and in time using plasmonic fields.

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Observation of 2D Cherenkov Radiation and its Quantized Photonic Nature

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The dimensionality of the medium into which free-electron radiation is emitted was predicted to fundamentally alter the radiation properties: its spectrum, intensity, directionality, and polarization. This is true for all forms of free-electron radiation, and particularly for Cherenkov radiation (CR). The CR first observed and explained over 80 years ago as an electromagnetic shockwave emitted by a charged particle when it exceeds the phase velocity of light in a medium [1]. Since then, CR has been mostly conceived as a 3D phenomenon where the radiation creates a cone around the emitting particle. Theory papers predicted two-dimensional CR (2D-CR) to have a sharper bandwidth, emitted into longitudinal modes [2], but, so far, only phenomena analogous to it were demonstrated experimentally [3,4], and such radiation has yet to be observed.

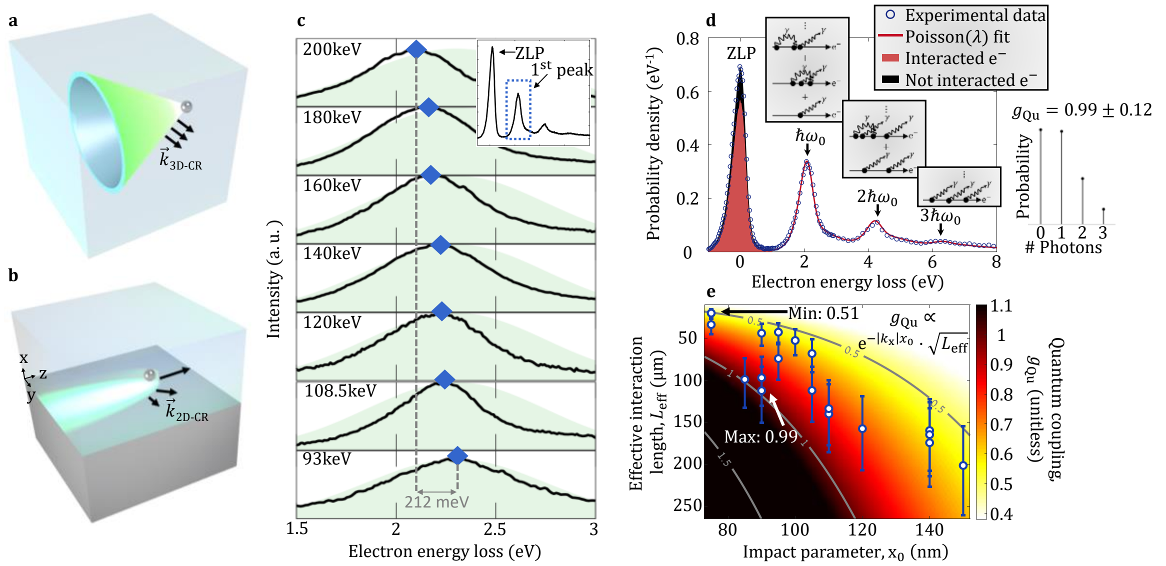

Figure 1 | The effect of dimensionality on Cherenkov radiation (CR). **(a)** Schematics of 3D-CR: wide-bandwidth emission forming a 3D cone. **(b)** Schematics of 2D-CR: narrow-bandwidth emission confined to a surface. **(c)** Measured electron energy-loss peaks that correspond to single-photon emission events, showing a blue-shift with decreasing electron energy following the Cherenkov condition with the dispersion of the surface photonic mode. These measurements constitute the first observation of 2D-CR. **(d) Resolving quantized emission events in coherent cathodoluminescence**. The inset on the right shows the integrated probabilities, corresponding to a quantum coupling strength of unity. **(e)** A map summarizing the quantum coupling strengths extracted from different measurements with 200 keV electrons as function of the impact parameter and interaction length.

We present the first observation of 2D Cherenkov radiation, wherein free electrons emit multiple quanta of surface photonic quasiparticles into a dispersion-engineered structure. The reduced dimensionality enhances the electron-photon interaction, allowing us to unveil the quantum photonic nature of the interaction and providing evidence for a recent paradigm shift in free-electron radiation: instead of emitting classical light, electrons become entangled with the photons they emit [5-7].

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Quantum-Classical Transition Exhibited in Micro Sphere Optical Modes Exited by Relativistic Electrons

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The particle-wave duality of a quantum object defines its behavior and demonstrates the quantum-to-classical transition exhibited in a case of quantum collapse. Experimenting with cathodoluminescence (CL), which is light emission by an electron beam, can address such a quantum-classical phenomena in two length scales, the photonic micron wavelength and the picometer electronic wavelength.

This work investigates theoretically electron-photon states through the coupling between relativistic electrons and photon modes in glass microspheres. The long lifetime and transverse coherence of the so-called whispering gallery modes (WGM) allow for properties of CL radiation in the far filed to be directly linked with the excitation in the sphere. We model an electron beam in a spatial superposition, for which the quantum or classical behavior of this system is the spatially coherent summation of the radiation from the two electron paths vs. the incoherent summation of their intensities.

We were motivated by the recent work of Remez [1] which showed experimentally that for such a superposition electron beam, the radiation from a metallic grating is summed incoherently. We believe that a fully quantum behavior can be observed with WGM-mediated CL.

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MEASURING THE MEAN INNER POTENTIAL OF BERNAL GRAPHITE USING OFF-AXIS ELECTRON HOLOGRAPHY

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Abstract

The mean-inner-potential (MIP) of a crystal is the average electrostatic Coulomb potential within a crystal with respect to vacuum. The MIP is a fundamental material property which reflects chemical-bonding and crystallographic surfaces [1].

We conducted off-axis electron holography experiments on highly-oriented-pyrolytic-graphite (HOPG) in a transmission-electron-microscope to measure the MIP from nanometer-scale volumes of Bernal graphite oriented with respect to the electron beam, along the principal axis or directions in the basal plane. These MIP were related to mean orbital electron radii and diamagnetic susceptibilities in perpendicular planes. Such intrinsic property measurements are challenging because of defect-induced interfaces at basal planes [2, 3]. Indeed, our structural examination of HOPG show stacking faults and planar rotations around the principal-axis, such that measuring intrinsic properties requires probing a volume of $\sim 10^2 \times 10^2 \times 10^2 nm^3$.

Experiments on individual Bernal graphite crystals with (0001) basal, or (1-100), (2-1-10) prismatic planes, resulted in MIP of 10.16±0.40V, 11.37±0.35V, 12.66±0.41V, respectively [4]. First-principles calculations from crystalline slabs [4] confirm these anisotropic measurements with 11.72V, 13.65V, 14.56V, respectively. Additionally, these experiments enabled to measure the mean free path for inelastic scattering in graphite of 197keV electrons at a collection angle of 18mrad resulting in 150.6±2.0 nm.

These measured MIP enable to determine projected mean radii of electron orbitals and volume susceptibilities (SI), assuming spherically symmetric charge distribution, at 0.704±0.015Å, $(-1.99\pm0.08)\times10^{-5}$; 0.744±0.015Å, $(-2.23\pm0.07)\times10^{-5}$; 0.785±0.015Å, $(-2.48\pm0.08)\times10^{-5}$.

The measured orbital radii and diamagnetism in the basal plane are comparable to expected values for carbon σ-bond hybridization [5-6]. Increased MIP on prismatic planes is related to s-orbital components, which decrease due to delocalized electrons between basal planes.

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Quantitative CL in SEM for characterization of high TC superconductors

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Cathodoluminescence (CL) in the Scanning Electron Microscope (SEM) was studied on bulk and thin film high Tc superconductors of Bismuth and YBCO phases. The goal was to differentiate between intrinsic and extrinsic (defects and foreign phases) properties and correlate them with macroscopic conductive transport measurements such as critical current and resistive broadening in magnetic field.
The CL in SEM study included: (1) Spectral CL and CL lifetime measurement of foreign phases (2) Spectral CL characterization of substrate defects and their effect on local thin film growth (3) Analytic CL calculation based on Monte-Carlo simulation of electron-hole depth profile in YBCO thin films (4) Thickness variations and surface coverage of thin films based on quantitative CL substrate intensity measurement.

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Investigation of Plasmonic Bloch Modes by Complementary Cathodoluminescence and Optical Dark-Field Spectroscopy Measurements

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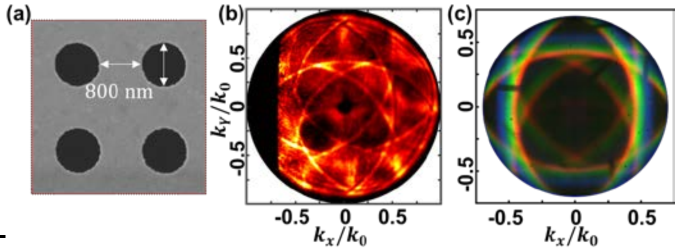

(a) SEM image of the plasmonic gold lattice. (b) Angle resolved CL and (c) DF images.

Photonic crystals are widely used to mold of the flow of light. Merging surface plasmon polaritons with photonic crystals enables the control of the optical density of states and enhances the already strong electron-light interactions in plasmonic systems [1]. Even in the seemingly simple structure of a periodic square lattice of holes within a thin gold film this interaction leads to a broad variety of plasmonic Bloch modes, distinguishable by their momenta and polarization. Therefore, the response of the system to excitation is formed by a superposition of these modes and with their wavelengths being at the order of the hole size and lattice constant, investigation beyond the dipole approximation is possible. In this work, we use cathodoluminescence spectroscopy (CL) for imaging the spatio-spectral near-field distribution of the optical Bloch modes in the visible to near infrared spectral ranges [2]. In addition, polarization-selective optical dark-field microspectroscopy (DF) is used to decompose the superposition of the plasmonic Bloch modes. Strong indication is found that the dominating signal is formed by radiating magnetic moments within the holes. Fourier optics and angle-resolved cathodoluminescence mapping reveal similar interference fringes in the far-field reciprocal space, suggesting propagation of surface plasmons along the surface and scattering by holes.

Our results visualize the responses of a plasmonic crystal to two different excitation techniques, an incident electron beam and an oblique illumination with white light, and show their comparability. The complementary use of cathodoluminescence spectroscopy and optical dark-field microspectroscopy is added to the range of methods to investigate plasmonic Bloch modes and - in the bigger picture - light-matter interactions in both real and reciprocal spaces.

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Pulsed-Laser Phase Plate for UEM: Theoretical Feasibility

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Interest is growing around developing imaging techniques for non-absorbing weak-phase objects, as many biological samples, since conventional amplitude contrast methods cannot generate in-focus image contrast. Zernike phase contrast microscopy proved to be a promising technique for producing high-resolution images of transparent objects in electron and optical microscopes. This method uses a λ/4 phase plate inserted in the back focal plane to apply a uniform quarter-wave phase shift to electrons scattered by the sample relative to the unscattered beam. Thin amorphous carbon films are generally employed as Zernike phase plates. However, material devices feature a short lifetime and inevitably induce unintended electron scattering and image distortion due to electrostatic charging. Moreover, matter-based methods for phase manipulation can only provide a fixed phase variation, always accompanied by undesired losses of a beam fraction.

As electron-optical equivalent of the phase-contrast light microscopy, we propose using time-dependent electromagnetic fields of ultrashort laser pulses to control the quantum-mechanical phase of electron pulses. Light-based phase plates would ensure a stable, tunable phase shift, enabling overcoming all the limitations of material devices. We present a theoretical model showing that the ponderomotive interaction between electrons and a high-intensity strongly-focused laser beam can be used to develop a non-material phase plate. This contribution presents a flexible calculation method to model the interaction, in which we derive a quantal phase from the classical action integral along the relativistic classical path. Results extend to realistic configurations of the electromagnetic fields of a pulsed laser beam. Our model proves that a phase shift of $\pi/2$ can be achieved by focusing the laser pulses produced by a fs-oscillator to a waist size of 2λ. Additionally, the high repetition rate (70-90 MHz) provided by the femtosecond mode-locked laser oscillator enables developing electron-optical elements to be applied routinely in ultrafast electron microscopy. Details on the experimental realization of the proposed puled-laser phase plate are provided in the contribution “Pulsed-Laser Phase Plate for UEM: Experimental Realization”.

Creation of Photonic Cat and GKP States Using Shaped Free Electrons

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Cat states and Gottesman-Kitaev-Preskill (GKP) states play a key role in quantum computation and communication with continuous variables. The creation of such states relies on strong nonlinear light-matter interactions, which are widely available in microwave frequencies as in circuit quantum electrodynamics platforms. However, strong nonlinearities are hard to come by in optical frequencies, severely limiting the use of continuous variable quantum information in the optical range. Here we propose using the strong nonlinear interaction of free electrons with light as a source for optical cat and GKP states. The strong nonlinearity can be realized by phase-matched free-electron interaction with photonic structures such as optical waveguides and microcavities. Our approach enables the generation of optical GKP states with above 10 dB squeezing and fidelities above 95% at post-selection probability of 10%, even reaching >30% using an initially squeezed vacuum state. Furthermore, the free-electron interaction allows for conditional displacements on the photonic state, enabling free-electron-based error correction schemes. Since electrons interact with light of arbitrary frequency, our approach can be used for the generation of cat and GKP states over the entire electromagnetic spectrum, from radio-waves to X-rays.

Electron pulse compression with terahertz electromagnetic fields

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Ultrafast Electron Diffraction and Microscopy techniques enable the visualization of atomic processes on their intrinsic temporal and spatial dimensions. A main limiting factor regarding the temporal resolution of these techniques is the duration of the electron pulses probing the material under investigation. Shortening electron pulses to durations that are on par with current laser pulses of few femtoseconds and possibly below will enable even deeper insights into the most fundamental light-matter interactions.

The limiting factors to electron pulse durations can be manifold, but for low-charge pulses typically the main contributor is dispersion. Time varying electromagnetic fields interacting with the electron pulses allow for the compensation of this detrimental effect. While state-of-the-art microwave systems for electron pulse compression suffer from the almost inevitable electronic jitter, optics-based approaches allow for passive synchronization of the whole electron-laser system [1].

Here, an all-optical system for the compression of electron pulses using laser-generated terahertz radiation is described. Emphasis is on the tailored interaction between electron and terahertz pulses by means of a freely rotatable semi-transparent mirror, the system's few-fs passive temporal stability and its demonstrated capabilities in compressing electron pulses from a duration of ~500 fs down to less than 30 fs [2].

This system is also utilized as a time-of-flight electron energy spectrometer of few-eV resolution (and possibly below) [3] with potential applications in time-resolved electron energy loss & gain spectroscopy.

Lastly, by tuning the electron-terahertz interaction geometry, specifically shaped electron pulses can be created. This is demonstrated by the controlled generation of compressed and tilted electron pulses. Experimental and theoretical studies [4] reveal a link between the pulse's tilt angle and its angular dispersion –a relation previously known only for optical pulses. The results of these experiments are the first indication for this principle also to hold for matter waves.

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An ultrafast source of attosecond electron pulses triggered by a surface plasmon

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Studies of electron dynamics on the femtosecond and attosecond time scale require extremely high temporal and spatial resolution and strong sensitivity to charge. Inline electron holography is an approach that fulfills these criteria [1]. Steady-state holographic imaging with low-energy electrons achieves a spatial resolution on the order of 1nm and enables observation of individual charges [2]. For studies of fundamental interactions and phenomena that have a short lifetime, such as trions and plasmonic fields, a source of ultrashort electron pulses is required.

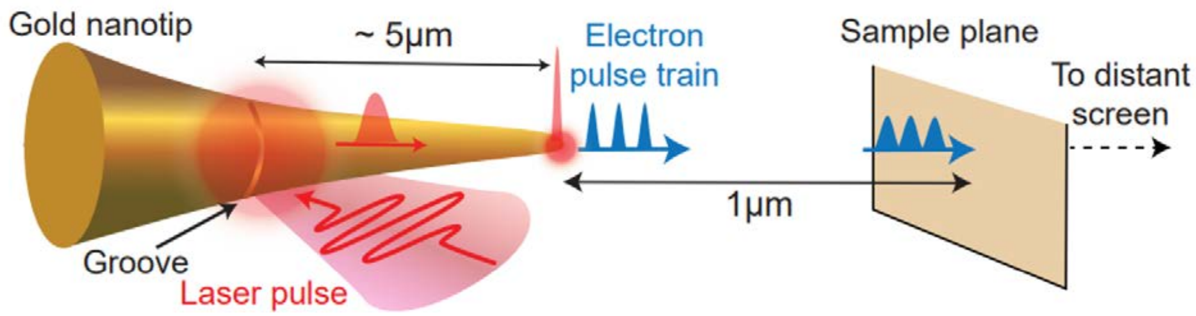

***Figure 1**. Sketch of the ultrafast electron emission by a surface plasmon. An ultrafast laser pulse hits a groove on the shank of a gold nanotip resulting in a surface plasmon. This plasmon concentrates on the apex and emits an electron pulse*

In this work, we devised and implemented an improved way to achieve a point source of ultrafast electron pulses towards nanometer spatial and femtosecond to attosecond temporal resolution. We couple a 6fs laser pulse to a single groove on the shank of a Au nanotip, which causes the excitation of a surface plasmon wave (see Fig. 1). The wave localizes at the nanotip apex [3], leading to the emission of an electron pulse. At low laser powers, we find multiphoton photoemission which has femtosecond time resolution linked to the initial laser pulse. At higher laser powers we find a strong deviation from the multiphoton power-law scaling of the emission current. We interpret this as a signature of the transition into the tunneling regime of electron emission where electrons are emitted in sub-cycle bursts with attosecond duration.

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Slow-electron PINEM and its anomalous Wannier-Stark localization in synthetic space

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The interaction between fast electrons and nanostructure-enhanced optical near-fields was studied extensively in the last two decades. Usually, the free electron kinetic energy and optical field strength are 100-200 keV and 0.01-1 V/nm, respectively. Thus, the ponderomotive term (A^2) and the asymmetry of quantum recoil between emission and absorption of photons are negligible.

Here we investigate the strong-field interaction of extremely slow electrons (~100 eV) with laser-induced near-fields (~V/nm) from a theory perspective. We find that a slow electron enables exotic spectral localization dynamics in the PINEM synthetic space, compared to fast-electron PINEM, which originates from the contributions of a non-negligible ponderomotive term and an asymmetric quantum recoil. We demonstrate that, starting from the non-relativistic Schrödinger equation, inducing a linear phase mismatch between electron and near-field results in Bloch oscillations in slow-electron PINEM. In synthetic space, despite fast-electron PINEM exhibiting symmetric oscillations, slow-electron PINEM exhibits asymmetric oscillations and localizations, as shown in Fig. 1. This asymmetry manifests as a difference in probability amplitude for absorbing or emitting photons by the slow electron, a behavior caused by the large group-velocity dispersion of free electrons expanding at small kinetic energies. We also find conditions for a quadratic phase mismatch regime. Here, an initially localized Wannier wavefunction in PINEM synthetic space exhibits dynamics of harmonic oscillations while retaining its Wannier-Stark spectral confinement. On top of asymmetric Bloch oscillations, we find an anomalous redshift in the period of the oscillations. This novel synthetic localization and oscillation behavior allows for improved coherent modulation of the PINEM spectrum. It might also enable explorations of basic condensed matter physics due to its analogous behavior to slow-electron PINEM.

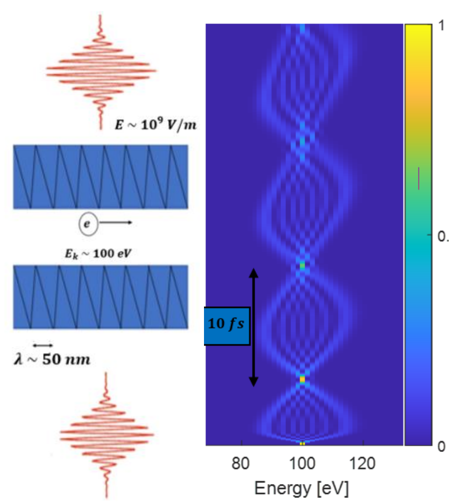

Figure 1: System setup & non symmetric Bloch oscillations

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Numerical Simulation of Multi PINEM Electrons in Free Electron Bound Electron Resonant Interaction

Aharon Friedman and Yali Carmon

We present a numerical simulation of the interaction of multiple free charged particles with a two-level system. The free electrons are moving at a mildly relativistic speed. The free electrons are pre-modulated via a PINEM process. The distance between the free electron and the TLS is much larger than the radius of the atom.

We developed a one-dimensional relativistic equation for the electrons. The Coulomb interaction is represented by a modified (exact) Darwin Hamiltonian.

The simulation encompasses several thousand electrons. This is a realistic figure. We follow the development of the TLS excitation, as well as its entanglement with the free electron.

Theory of Ponderomotive Transverse Electron Beam Shaping

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Electron-Photon interactions are at lowest order limited to second order effects and commonly described by the ponderomotive potential. The presented theoretical description, bound by the experimental framework, considers a pulsed electron beam in a modified SEM set-up modulated by a high intensity pulsed laser light field in parallel propagation. Therein, the transverse phase modulation of a relativistic electron is realized by an effective scattering phase $\varphi_v(x,y)$. Due to the vanishing of first order effects in the interaction Hamiltonian, the Dirac equation can be reduced to an effective Schrödinger equation [1] and using a pulsed light field within the potential leads to the effective scattering phase [2]:

$$\varphi_v(x,y) = -\frac{\alpha}{2\pi(1 \pm \beta)} \frac{E_L}{E_e} \frac{\lambda_L^2 \, I(x,y)}{\int dxdy \, I(x,y)}$$

Both a ray as well as a wave optics simulation were implemented to compare the theoretical description to experimental data as shown in fig. 1. Ponderomotive wave front shaping may enable aberration correction, the creation of exotic electron beams and the realization of adaptive electron microscopy.

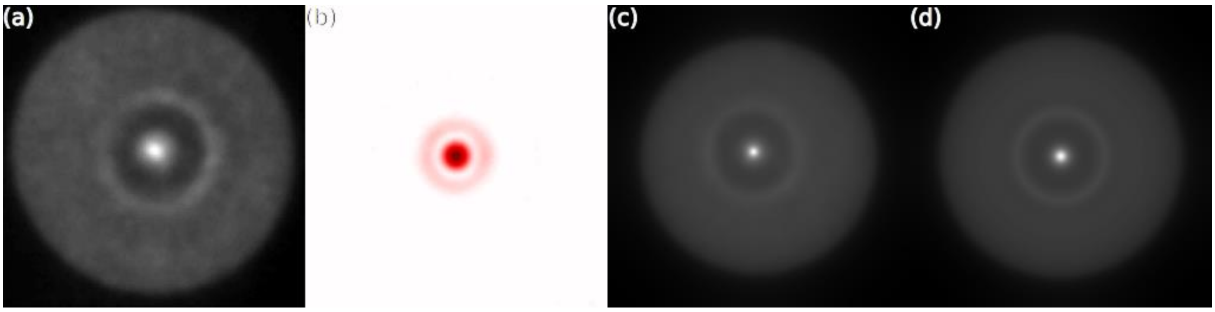

Figure 1: a) Experimental measurement of the electron distribution on the MCP after electron-photon interaction. b) Measured light intensity pattern in the interaction region. c) Ray optics simulation using b. d) Wave optics simulation using b.

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Imaging the field inside dielectric laser acceleration nanostructures

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Dielectric laser acceleration (DLA) promises a compact and cost-efficient alternative to conventional radiofrequency-based particle accelerators [1]. Efficient electron acceleration in such compact devices critically depends on achieving nanometre control of electron trajectories by precisely designed optical nearfields inside the DLA structure [2]. However, these nearfields have so far been inaccessible due to the complexity of DLA devices and their geometrical constraints, hampering efforts to design and optimize future DLAs. Here we present the first measurement of the field distribution inside a DLA channel, which we extract from the measured acceleration distribution of the electrons. What enabled such a measurement is the development of a novel microscopy approach based on photon-induced nearfield electron microscopy (PINEM), achieving deep-subwavelength imaging of the internal DLA nearfield for each excitation wavelength. We applied this approach to two leading DLA designs: a dual-pillar structure with distributed Bragg reflector and an inverse-designed resonant structure [3]. Our experiments complement full 3D simulations and unveil surprising deviations from the expected designs, showing complex field distributions that we can relate to the 3D nature of the device and its fabrication tolerances. We further envision a tomography method to image the 3D field distribution, key for the future development of high-precision DLAs. Our method could image the field distribution inside other complex nanophotonic devices and microstructures that are typically too large for conventional nearfield optical techniques.

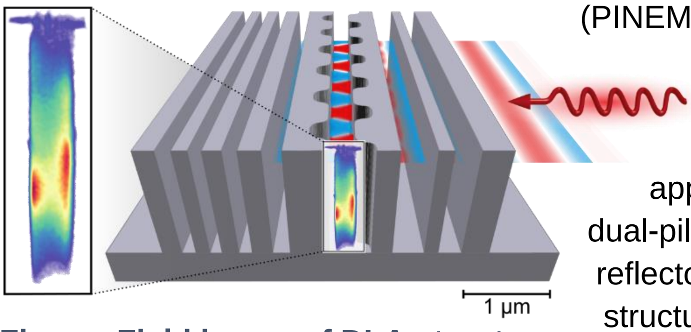

Figure: Field image of DLA structure.

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Photon-Induced Near-Field Interaction in Ultrafast Low Energy Electron Microscopy

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The coupling of free electrons to localized optical near fields has enabled the development of novel types of ultrafast electron microscopes. Swift electrons, with kinetic energies in the 100 keV-range, are readily used in photon-induced near-field electron microscopy (PINEM) to investigate nano-sized systems with excellent spatial and spectral resolution.
For swift electrons the coupling efficiency to a single nanoconfined optical mode, however, is inherently weak. The use of much slower electrons may boost the interaction time and thus enhance the near-field interaction, in particular for small nanostructures for which phase-matching conditions are readily fulfilled. So far, however, PINEM effects could not yet be resolved experimentally, in ultrafast low-energy electron microscopy.
Here, we report the first observation of PINEM-like interactions in an ultrafast point-projection electron microscope (UPEM). Plasmonic nanofocussing based photoemission from a sharp gold nanotip is used to generate ~30fs electron pulses. Those electrons are accelerated by a -100V bias voltage towards a 13nm thick freestanding gold film. A Yagi-Uda like antenna structure is milled into the film, supporting optical field confinement under excitation by a 20fs optical pump pulse centered at 1900 nm. A magnified shadow image of the electrons transmitted through the antenna is formed on a time-of-flight delay-line detector, recording their complete 3D momentum distribution. We observe a spread of the electrons momentum distribution in flight direction caused by longitudinal electric field components of the near field, similar to experiments with swift electrons. Additionally, we also see large sideways deflection of the electrons by transverse field components. This may open up the way to a spatial and temporal characterization of vectorial near fields.

Pulsed Laser Phase Plate for UEM: Experimental Realization

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When Zernike invented the phase plate for the optical microscope, it revolutionized the imaging of soft (biological) samples. Several years later, a phase plate for the electron microscope has been realized. Since then, different types of phase plates have been conceptualized, each with their own advantages and disadvantages.

Recent theoretical work, performed in our group, has shown that it is possible to use a pulsed laser to induce phase shifts in electrons. Using the ultrashort pulses from present day oscillators should allow us to create a pulsed laser phase plate inside an electron microscope. This type of phase plate would avoid the limited lifetime and additional scattering matter-based phase plates suffer from. Further details on the theory can be found in the poster 'Pulsed-Laser Phase-Plate for UEM: Theoretical Feasibility'.

This contribution focuses on the experimental realization of this project. The pulsed laser phase plate requires spatial and temporal alignment, down to micrometer and femtosecond levels. The TEM utilized in our group is modified with a microwave cavity, which enables us to create electron pulses of some tens of femtoseconds pulse length, and at a 3 GHz repetition frequency. This allows us to reach a high throughput in our microscope. A demonstration of the obtained alignment is given by the observed Photon-Induced Near-field Electron Microscopy effect. Future work will focus on implementing the configuration needed for the pulsed laser phase plate.

Towards Driving Quantum Systems with the Non-Radiating Near-Field of a Modulated Electron Beam

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When manipulating quantum systems with electromagnetic radiation, the spatial resolution is limited by the Abbe limit. To overcome this limitation, we have developed a fundamentally new approach, in which we coherently transmit electromagnetic excitation through the non-radiating near-field of a modulated electron beam. This approach could open a path to spectrally selective quantum control with nanoscale spatial resolution by exploiting the small de Broglie wavelength of electrons.
In a proof of principle experiment we use a spatially modulated electron beam of a fast cathode ray tube from an analog oscilloscope to coherently drive the hyperfine levels of 39 K. Deflection of the electron beam in multiple directions even allows to paint potentials to even mimic polarized light in the microwave range.
In a second experiment, we will realize Electron Spin Resonance by replacing the atoms with a solid radical sample (BDPA). In this experimental realization a microcoil is used to detect the decay of the excited spins.

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Applications in Electron Microscopy for Electron-Photon Correlations

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Recent experiments demonstrating strong coupling between optical modes and free electrons open the door to a new generation of studies on quantum information and communication using photon-electron entanglement. There are also a number of potential applications for photon-electron correlation in imaging, which could provide strong motivation for incorporating photonic systems in the next generation of electron microscopes.

Time-correlated photon-electron pairs can be used to create heralded particle sources. One figure of merit for heralding is the Klyshko efficiency, which measures the fraction of coincident photon and electron detection events. Another metric is the fractional reduction in shot noise. We describe the mathematical relationship between these two heralding metrics and consider their respective applications. As an example, we evaluate the possible improvement in the signal-to-noise ratio for dose-limited transmission electron microscopy using a photon-heralded electron source to register inelastic interactions with the sample. We will also describe new imaging schemes which could simplify electron microscope architecture.

Finally, we discuss benchmark values for the engineering parameters required to enable these applications, including photon-electron coupling strength, detection efficiencies, and dark count rate.

Sub-optical-cycle electron pulse trains from metal nanotips

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The coherent modulation of swift electron beams with strong laser fields [1] has enabled the generation of attosecond electron pulses [2], opening up new research avenues in ultrafast science. Here we study a comparatively simple alternative, the production of electron pulse trains directly at the source [3]. In our theory work, we show that sub-optical-cycle electron bursts induced by tunneling photoemission from a metal nanotip [4,5] can retain the temporal fingerprint of their emission dynamics in a typical low-energy point-projection microscope setup [6] (see Fig. 1(a)).

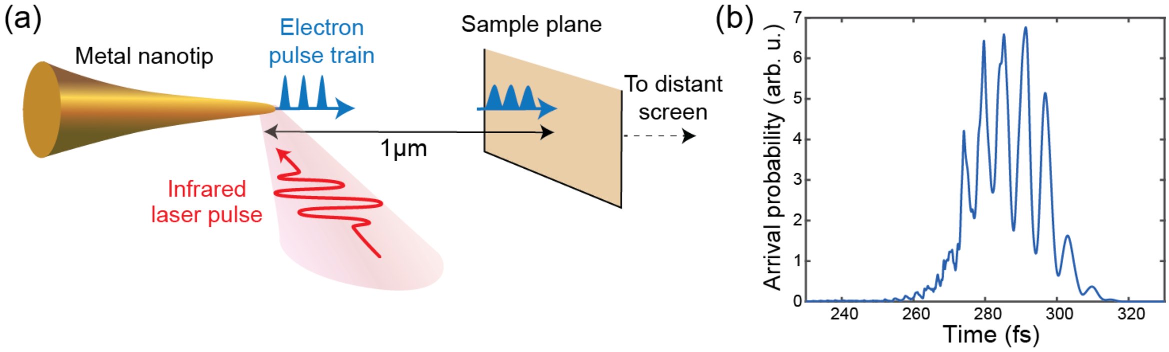

Figure 1*. (a) Sketch of the ultrafast electron point-projection microscope setup (not to scale). The nanotip emitter is triggered by a surface plasmon. (b) Arrival probability of an attosecond electron pulse train at the sample plane (1550nm laser pulse).*

Figure 1(b) shows a typical arrival probability of the electron wavepacket at the sample, calculated using the time-dependent Schrödinger equation. Our results show that strong acceleration by a static field, a short propagation distance and a sufficiently large optical cycle duration mitigate temporal smearing due to matter-wave dispersion. Our approach enables studies of coherent interactions of slow electrons with matter on sub-femtosecond and nanometer scales, a regime which has hitherto remained inaccessible.

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Cathodo- and photoluminescence characterization of single photon emitters

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In this project, we aim to compare both cathodo- and photoluminescence (CL, PL) measurements to investigate single photon sources. For PL measurements, we use a transmission setup in an inverted optical microscope, with a lensed single mode fiber for excitation and the microscope objective for collection. This setup allows for configuring individual emitters and enhancing the excitation efficiency. We also compare our PL measurements with CL measurements of individual emitters and differentiate the spectral broadening happening in CL measurements due to the electron beam inelastic scattering events in the sample and different mechanisms of radiation. In both setups, potential single photon sources are characterized with a spectrometer and a Hanbury-Brown-Twiss experiment for intensity correlation/g^2-function measurements.

Nanosecond Electron Pulse Production via Schottky-enhanced Photoemission

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Nanosecond electron pulses can support high pulse currents for time-resolved, single-shot measurements of biological and condensed matter systems [1] and could also be well-suited to emerging quantum electron microscopy techniques including multi-pass transmission electron microscopy [2,3]. Here, we report on the characteristics of a new regime of nanosecond photoemission from a 540 nm Schottky emitter at 1300 K. Photoemitted electrons are dispersed according to their energies by a magnetic prism array and imaged on a scintillating YAG screen. We have demonstrated that high current electron pulses can be emitted promptly during 1 ns laser pulses. We find that the pulse current incident on the YAG screen increases linearly with the laser pulse energy and have measured pulses of single to tens of electrons generated by nJ laser pulses. The distribution of electron energies narrows with decreasing photocurrent but remains broader than that of the continuous beam produced by the emitter at 1820 K by up to 0.5 eV. Furthermore, our fit of the measured photocurrent as a function of the angle between the laser polarization and the tip axis is dominated by a first-order process. We conclude from these results that single-photon absorption is sufficient for over-the-barrier electron emission in this Schottky-enhanced photoemission regime.

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Shaping of electron beams using sculpted thin films

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Electron-matter interactions and the wave nature of electrons allow for electron beam shaping by sculpted thin films. It can be used to develop technological applications in transmission electron microscopy (TEM) that offer increased resolution in different imaging modes and thus to improve measurement techniques. In this poster, we present preliminary results of two such applications. First, we show spherical aberration correction of field-free STEM mode in FEI Titan G2 Holo microscope by eliminating the spherical wavefront of the electron beam focused by the C3 lens. Such an application may lead to spherical aberration corrected Lorentz STEM, used for measurements of magnetic materials, which, nowadays, is impossible in many systems because even if a multipole aberration corrector is installed in them, their condenser lenses aren't strong enough to focus the beam onto it. Second, and towards the correction of chromatic aberration of STEM, we use thin film diffractive electron lenses to chromatically manipulate a focusing electron beam wavefront. Practically, we fabricated diffractive lenses which their focal lengths are dependent on the electron beam energy, changing the total focus of a TEM beam at Low Angle Diffraction (LAD) mode when they are placed at the sample holder. Due to fabrication limitations chromatic aberration correction may be impractical in the present, but this work may be a proof of concept and pave the way towards such achievements in the future.

Observations of Bohm Trajectories in Surface Gravity Water Waves

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Abstract:
We observe Bohm trajectories of different initial states, such as the two slits, in a system of surface gravity water wave packets. This system is governed by a wave equation that is identical to the Schrödinger equation in optics or quantum mechanics and enables to utilize the Bohm formalism for classical waves. The quantum potential analog can be reconstructed from our measurements and is compared it to the theoretical predictions.

1. Introduction

The time evolution of a wave function in quantum mechanics is analogous to that of surface gravity deep water wave pulses along the propagation coordinate. Moreover, an effective linear potential can be infused in the water tank using a computer-controlled pump. This setup represents the hydrodynamic analog to a freely falling quantum mechanical particle in a gravitational potential. In this experiment, we have recently measured, for the first time, the cubic *Kennard phase* which was predicted in 1927, for both Gaussian and Airy wave packets [1,2]. Inspired by these successful experiments, we now study other analogies between quantum mechanics and gravity water waves, and in particular Bohm trajectories and their corresponding quantum potentials. The de Broglie–Bohm theory, is an alternative interpretation, with respect to the Copenhagen interpretation of quantum mechanics. It assumes that the propagation dynamics (in time or in space) can be obtained by forming a wavefunction-dependent potential that guides particles along specific trajectories [4]. Bohm trajectories for a single photon in a two-slit experiment were studied earlier by weak value measurements [5]. Here instead we utilize the full knowledge of the wavefunction in every location in the tank in order to observe the Bohm trajectories for different cases of initial states.

2. Methods

For surface gravity water waves, the scaled spatial version of the modified Schrodinger equation for the normalized amplitude envelope $A \equiv A(\tau,\xi)$ in the moving frame with the group velocity c_g is given by

$$i\frac{\partial A}{\partial \xi} = \frac{\partial^2 A}{\partial \tau^2}$$

The scaled dimensionless variables ξ and τ
are related to the propagation coordinate x and the time t by $\xi \equiv \varepsilon^2 k_0 x$ and $\tau \equiv \varepsilon\omega_0(\frac{x}{c_g} - t)$. The carrier wave number k_0 and the angular carrier frequency ω_0 satisfy the deep-water dispersion relation $\omega_0^2 = k_0 g$, with g being the gravitational acceleration; the group velocity $c_g \equiv \frac{\omega_0}{2k_0}$.
The parameter $\varepsilon \equiv k_0 a_0$ characterizing the wave steepness is assumed to be small $\varepsilon \ll 1$ in the linear regime.
One can notice that for spatially evolving surface gravity water waves, time and space are interchanged with respect to their role in quantum mechanics. Hence, the modified Bohm's equation of motion is:

$$\frac{dr_j}{d\xi}(\tau,\xi) = \frac{2Im\nabla_\tau A(\xi,\tau)}{A(\xi,\tau)},$$

where dr_j are the surface gravity water wave trajectories. It is worth to mention that at the transition from quantum mechanics to surface gravity waves, the coefficients take the form $\hbar \to 1, m \to \frac{1}{2}$ and $\nabla_\tau = \frac{d}{d\tau}$ [6].

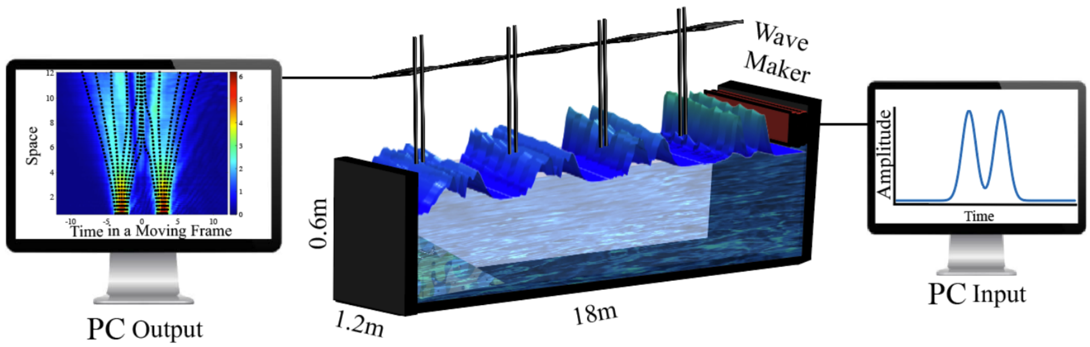

Figure 1: The concept of the experiment: two slit wave packets are generated by a computer-controlled wave maker. These wave packets evolve in the water wank and their complex wavefunction is measured by the wave gauges. The Bohm trajectories are extracted from the complex wavefunctions.

3. Results

The experiments discussed in this paper were performed in a 18m long, 0.6m wide, and h=0.6m deep laboratory wave tank, see Fig. 1. Water waves are generated by a computer-controlled wavemaker, placed at one end of the tank. The two slit experiment was performed with a temporal width of $t_0 = 1s$ and temporal distances $t_s = 4{,}6{,}8s$ for two slits. We also calculated and plotted the average of all Bohm trajectories $< r_j >$ for the two slit experiment. As it can be seen in Fig. 2 (white lines), the average trajectory follows a straight line which corresponds with the Ehrenfest theorem, i.e. the average trajectory is identical to the classical propagation of the particle which is in this case stationary owing to the fact that the particle exists a slit with zero momenta.

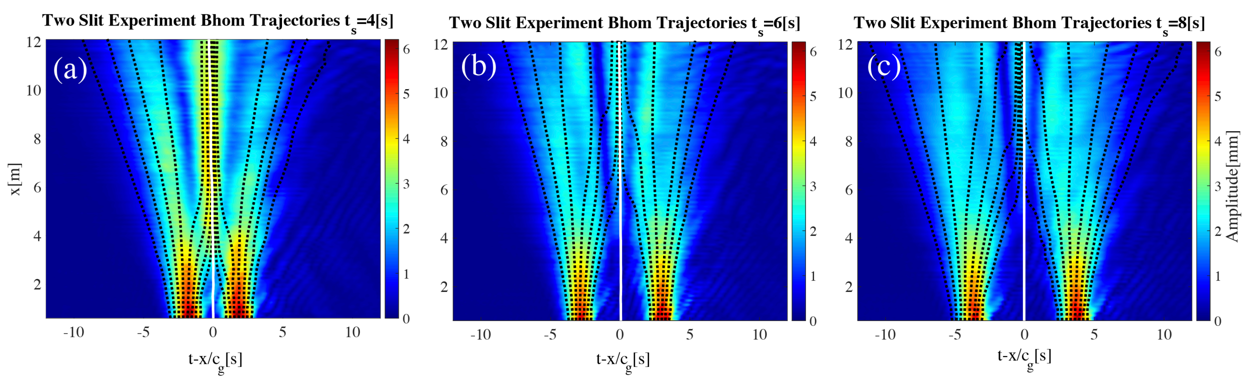

Figure 2: Two slit experiment for $t_s = 4{,}6{,}8s$. The dashed lines are the trajectories and amplidues are given by pseudocoeloms corresponding to $0 - 6mm$.

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Chip-based electrostatic Paul trap-like structures for electron beam manipulation

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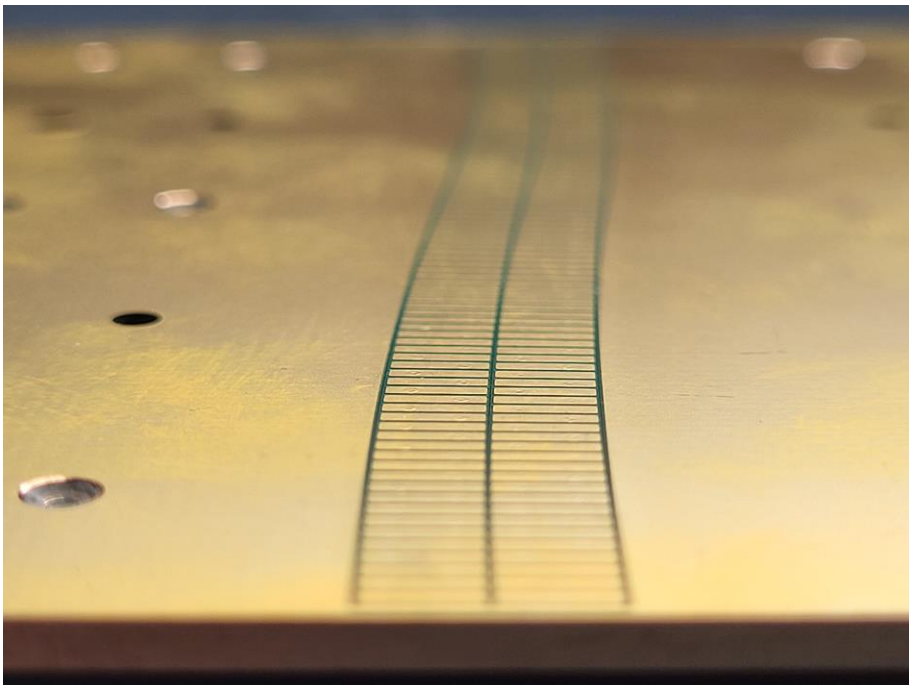
We show advances in complex free electron beam manipulation. For this, we use planar chip structures holding a multitude of electrodes generating *electrostatic* fields. In the frame of a moving electron these static fields appear like a temporally alternating field creating the same restoring pseudopotential like a Paul trap. We used tailored on-chip electrode layouts to guide electrons along a curve and measured the full first stability regime (a-q parameter set). High beam energies of up to 500 eV allowed us to perform the measurements in a standard scanning electron microscope (SEM), heralding new possibilities for complex electron beam control. Furthermore, we show preliminary results of a linear electrostatic electron resonator structure, with ramifications for a future quantum electron microscope.

Electron beam guiding in an auto-ponderomotive s-curved structure. The electrons propagate above the symmetry line between two opposing planar chips with matching electrode layout (second chip not shown).



Coherent Interactions Between Electrons and Photons in a 10 KeV Scanning Electron Microscope

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In recent years, there has been substantial progress in the coherent coupling of free electrons to light. Beginning with the pioneering work of Zewail et al. in developing photon-induced near-field electron microscopy [1], these interactions have been manipulated to create widely tunable light sources [2, 3], laser-based adaptive phase plates [4], attosecond-structured electron packets [5, 6], and most recently cavity-mediated electron-photon pairs [7].

Most of these previous efforts have taken place at high electron energies only accessible in large scanning transmission electron microscopes (STEM). For these concepts to be applied more widely, for instance in scanning electron microscopy and chip-scale devices, a means of operating at low electron energy will be required. In this work, we present our efforts to explore coherent electron-photon interactions at significantly lower electron energies. Specifically, we target 1 - 10 keV energy ranges found in our highly customized scanning electron microscope (SEM). This lower energy introduces a new range of challenges. For example, since the electrons now travel substantially slower than the speed of light, one cannot directly phase match into standard dielectric waveguides. We are trying to overcome these challenges by working with slow waveguide structures for electrons to efficiently couple into. Another challenge is that since these slow wave structures have significantly tighter evanescent optical fields, we must get the beam within nanometers of the structure without hitting it, leading to our development of active beam stabilization. Finally, due to the lack of commercial time-tagging electron spectrometers at SEM energies, we are developing one ourselves. By overcoming these challenges, we aim to bring heralded and non-classical photon and electron sources much closer to lower electron energies and thus much wider application.

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non-equilibrium theory of electron emission from metals

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We employ recent advances in our understanding of the electron non-equilibrium to provide a comprehensive theory of thermionic, field and photoemission from metals both for the ultrafast and steady-state regimes in the strong field limit. We discuss the relation of our findings to experimental measurements

Tunable Photon-Induced Spatial Modulation of Free Electron Wavepackets

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Spatially shaping electron beams has great importance in industrial and academic applications, such as nanolithography, microscopy, material studies and fabrication inspection. To this end, the frontier of research in recent years has been spatial coherent shaping, achieved via phase and amplitude holograms for electrons [1-3]. Recently, a new method to generate such spatial electron modulation was proposed, based on the ultrafast interaction of electron pulses and near-field electromagnetic waves [4,5], attracting attention for the ability to correct and purify electron beams [6,7]. Tunable spatial modulation of electron beams, on the other hand, is still an open challenge by any means [8] and has yet to be performed experimentally with electron-light interactions.

Here, we present active spatial modulation of electrons by engineering their interaction with ultrafast surface plasmon interference patterns in an ultrafast transmission electron microscope (UTEM). First, in the low intensity regime, we directly determine the electron distribution through shaping of the plasmonic field, by engineering the plasmonic coupling slit or the polarization of the laser pulse impinging it. We further verify the coherence of the shaping process through electron diffraction. Thereafter, in the high intensity regime [9], we demonstrate how different interaction orders possess a different shape, while the entire electron distribution undergoes 2D spatial Rabi oscillations [10,11]. Our work presents new degrees of freedom to actively shape electron wavefunctions, with possibilities for improving state-of-the-art electron microscopy with tunable and tailored electron beams.

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Generating Spatially Entangled Qubits using Quantum Nonlinear Holography

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In nonlinear holography, specifically in nonlinear photonic crystals (NPCs), the spatial shape (both phase and amplitude) of different harmonics is generated from the fundamental harmonic entirely inside the NPC, by modulating the second order nonlinear coefficient [1]. Here, we experimentally observe its quantum counterpart for the first time, paving the way for compact and unique quantum light sources. We shape the spatial quantum correlations of entangled photon pairs generated in a type-2 spontaneous parametric down conversion (SPDC) process without any pump shaping. Since HG functions form a complete basis of orthogonal transverse modes, we can decompose the two-photon state generated by SPDC using HG ket vectors in momentum space q of the signal and idler waves. The coefficients of the decomposed state generally depend on the pump shape and the crystal modulation pattern. Our design aims to obtain a Bell state in the spatial domain, hence we would like to have only two non-zero coefficients. We designed and fabricated an HG_{01} shaped NPC (Fig. 1b) using electric field poling. Coincidence measurements were taken using the set-up in Fig.1.a. The highest coincidence counts are obtained for only two cases, when one of the two beams is an HG_{01} beam and the other one is an HG_{00} beam, as expected from the Bell state design. For comparison, we show the coincidence map of a regular PPKTP crystal, which is characterized by a single peak, in which both the signal and the idler are HG_{00} beams (Fig. 1.c.)

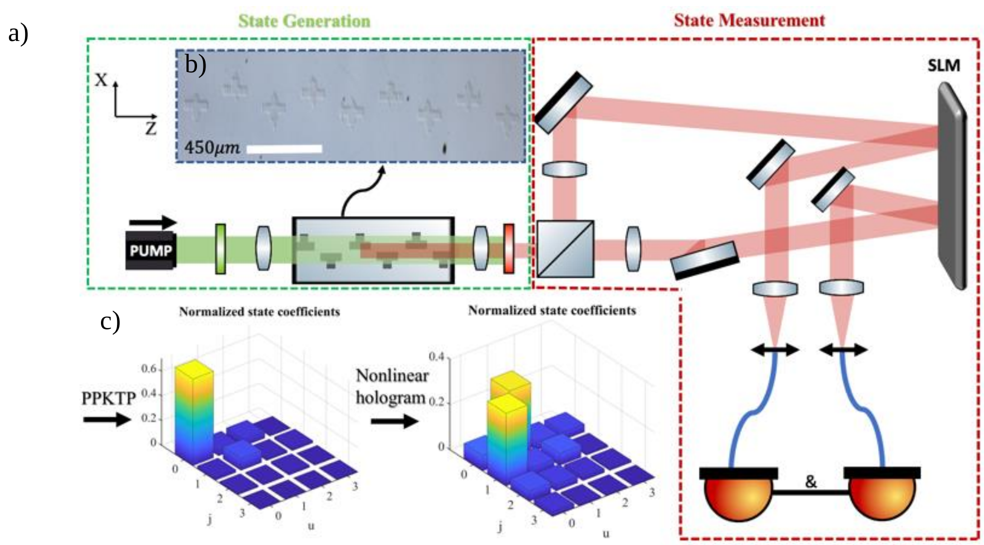

Fig. 1. a) Experimental setup. b) Microscopic picture of the top surface of the fabricated crystal c) Coincidence measurements, corresponding to the absolute value squared of the coefficients of the decomposed Bi-photon state. Left – regular PPKTP. Right - HG_{10} shaped nonlinear photonic crystal.

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Quantum electron wavepacket interaction with light and matter

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We explore the quantum aspects of the interaction between free electron with light and matter based on **the quantum electron wavepacket** (QEW) description. The QEW presentation delineate two limits of electron-light interaction: the point-particle-like classical regime and the plane-wave-like quantum regime. This demonstrates the universal quantum-to-classical theories transition, connecting the **Dielectric laser accelerator** (DLA) and **Photon-induced near-field electron microscopy** (PINEM).
We further extended the QEW based theory to interaction of free electron with single **two-level system** (TLS): **free- electron bound-electron resonant interaction** (FEBERI). A comprehensive energy conserving analysis of the entangled free and bound electrons relates the post-interaction energy spectrum of the QEW to the initial quantum (qubit state of the bound electron and can facilitate an application of interrogation and coherent control of the quantum (qubit) state of single TLS using shaped QEWs.

Interferometry viewed from phase space

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Among the different formulations of quantum mechanics, the arguably most illustrative one is based on *Wigner functions* [1,2]. Such a phase space description offers not only an intuitive picture, but also enables a deeper understanding of certain *quantum phenomena*. For instance, particular insights obtained in phase space have revealed the intriguing relationship between black hole physics and the elementary quantum system of an inverted harmonic oscillator [3].
However, the concept of Wigner functions is not sufficient to explain *interference phenomena* caused by the interplay of *two quantum systems*. In order to simplify the description of matter-wave interferometers in phase space [4-6], we thus introduce the *Wigner matrix*. For the first time, we present the dynamical equation [7] that governs the time evolution of its elements. We demonstrate that the *difference of two potentials* determines the off-diagonal elements of the Wigner matrix, and results in the *observable phase shift* of the interferometer. This feature is in sharp contrast to the *Liouville equation*, describing the dynamics of a *classical* phase-space distribution, where only the *force* enters directly. We relate our observations to the scalar *Aharonov-Bohm effect* and the *non-locality* intrinsic to quantum mechanics.

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On-chip ponderomotive optics for quantum electron microscopy

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This poster reports on progress made on charged particle beam guiding and splitting using ponderomotive potentials generated "on-chip" by electrostatic and electrodynamic potentials.

Based on the previous single-layer microwave structures [1-3], an electron beam splitter consisting of two printed circuit boards was developed, which allows splitting of an electron beam for electron energies up to 200 eV [4]. Other electrostatic counterparts to the microwave traps and beam splitters have been developed, which, although technically different, are based on the same physical principle. These electrostatic instruments can trap charged particles with very different masses in highly tunable potentials whose shape and strength can be locally adjusted by the layout of the lithographically fabricated electrodes, and the applied voltages can be adjusted. Measurements are shown that guide electrons and ions for a wide range of energies and masses (from 20 to 5000 eV and from $5 \cdot 10^{-4}$ to 131 u), and the splitting of electron beams into two output beams is demonstrated for energies up to the kiloelectronvolt range. [5-6]

It is shown theoretically that the miniaturization of these electrostatic structures leads to larger trap frequencies and thus to larger energy spacings between the states of motion of the particles in the effective potentials, which should make quantum mechanical phenomena such as interaction-free measurement with electrons observable in future experiments and pave the way for the realization of a quantum electron microscope [7].

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