ColdBeams 2017

International conference

July 10 – 12, 2017

on the campus of

Eindhoven University of Technology

Eindhoven, the Netherlands

http://www.coldbeams2017.nl/

Program and book of abstracts

Scientific committee

- Daniel Comparat, Laboratoire Aimé Cotton (FR)
- Francesco Fuso, University of Pisa (IT)
- Yuval Greenzweig, Intel Corporation (IL)
- Erik Kieft, FEI Company (NL)
- Jom Luiten, Eindhoven University of Technology (NL)
- Jabez McClelland, National Institute of Standards and Technology (USA)
- Ferdinand Schmidt-Kaler, University of Mainz (D)
- Robert Scholten, University of Melbourne (AUS)
- Adam Steele, zeroK NanoTech (USA)
- Matthieu Viteau, Orsay Physics (FR)
- Edgar Vredenbregt, Eindhoven University of Technology (NL)
- Kevin Weatherill, Durham University (UK)

Organizing committee

- Edgar Vredenbregt, chair
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- Peter Mutsaers
- Steinar Wouters

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Program

Sunday evening, July 9th

Time	Event
18:00	Welcome reception & registration (Grand Café de Zwarte Doos)
20:00	Closing

Monday morning, July 10th

Time	Code	Event/speaker	Chair/title
8:30		Registration	(Auditorium TU/e)
9:15		Conference opening	
9:25		Cold Ions 1	Edgar Vredenbregt
[25 min]	I1	McClelland	Cold atom ion sources
[25 min]	I2	Viteau	ColdFIB – a FIB column with a laser cooled source
[25 min]	I3	Wouters	Towards a high resolution Rb^+ FIB
[15 min]	O1	Johnson	A Low-Energy Antiproton Beamline for ALPHA-g
10:55	Coffee break		
11:30		Cold Electrons	Francesco Fuso
[25 min]	I4	McCullogh	Cold atom electron sources
[25 min]	I5	Franssen	The TU/e ultrafast and ultracold electron source
[25 min]	I6	Batelaan	Quantum degenerate electron beams
[15 min]	O2	Fedchenko	Time-of-flight microscopy implementation for the study of cold electron beam
13:00	Lunch break		

Monday afternoon, July 10th

Time	Code	Event/speaker	Chair/title
14:30		Cold Atoms	Daniel Comparat
[25 min]	I7	Ott	Electrons and ions meet ultracold atoms
[25 min]	I8	Eder	Atom Eyes: „Scanning HElium atom Microscopy”
[25 min]	I9	Pratt	Surface analysis of nanomaterials using a laser-cooled beam of spin-polarised metastable helium atoms
[15 min]	O3	Smits	Faraday waves in Bose-Einstein condensates
16:00	Coffee break		
16:30		Applications	Peter Mutsaers
[25 min]	I10	Greenzweig	Circuit Edit Challenges and Ion Beam Requirements
[25 min]	I11	Rue	Low-energy and high-resolution ion beams from an applications viewpoint
[25 min]	I12	Jamieson	Quantum computer devices built from shallow implanted single atoms
18:00	Buffet-style dinner		
18:00	Posters		
21:00	Closing		

Tuesday, July 11th

Time	Code	Event/speaker	Chair/title
9:00		Cold Ions 2	Jabez McClelland
[25 min]	I13	Steele	FIB Platform Employing a Low-Temperature Ion Source
[25 min]	I14	Comparat	Forced field ionization of Ry states for the production of monochromatic beams
[25 min]	I15	Sparkes	Disorder-Induced Heating in Ultracold Ion Beams
10:15	Coffee break		
10:45		Microscopy	Kevin Weatherill
[25 min]	I16	Schmidt-Kaler	Single ion microscopy
[25 min]	I17	Gnauck	Helium Ion Microscopy: High resolution Imaging and Nanomachining with He and Ne Ions
[25 min]	I18	Hommelhoff	Quantum electron microscopy – and on photonics-based electron beam control
[15 min]	O4	Juffmann	Multi-pass transmission electron microscopy as a tool for structural biology
12:15	Lunch break		
13:30		Alternate sources	Robert Scholten
[25 min]	I19	Kruit	Nano Aperture Ion Source
[25 min]	I20	Gierak	ElectroHydroDynamic emitters developments for improving Focused Ion Beam machines
[25 min]	I21	Vandervorst	SIMS analysis of advanced semiconductor materials and devices : present and emerging solutions.
14:45	Coffee break		Photo opportunity
15:15	Social program		
18:00	Drinks (restaurant De Kazerne)		
19:00	Conference dinner (restaurant De Kazerne)		
22:00	Closing		

Wednesday, July 12th

Time	Code	Event/speaker	Chair/title
9:00		Materials analysis	Yuval Greenzweig
[25 min]	I22	Tromp	Spectroscopy with the Low Energy Electron Microscope
[25 min]	I23	Grehl	Low Energy Ion Scattering – analyzing the outer monolayer
[25 min]	I24	Wirtz	SIMS performed on the Helium Ion Microscope: new prospects
[15 min]	O5	Verhoeven	A novel method for time-resolved electron energy loss spectroscopy using microwave cavities
10:30	Coffee break		
11:05		Ultrafast Electrons 1	Erik Kieft
[25 min]	I25	Ropers	Ultrafast Transmission Electron Microscopy with Laser-triggered Field Emitters
[25 min]	I26	Musumeci	Sub-10 fs relativistic electron beams with ultralow emittance for ultrafast electron diffraction
[15 min]	O6	Weppelman	Creating ultrafast electron pulses using a microfabricated laser-triggered Beam Blanker
12:10	Lunch break		
13:00		Ultrafast Electrons 2	Jom Luiten
[25 min]	I27	Baum	Electron microscopy of electromagnetic waveforms
[25 min]	I28	Musumeci	Ultra-High Brightness Electron Beams From Very-High Field Cryogenic Radiofrequency Photocathode Sources
[15 min]	O7	van Rens	Ultrafast Time-resolved Electron Microscopy using microwave cavities
[10 min]	Conference closing		
14:15	Visit to CQT labs (Cyclotron building)		

Practical information

Emergencies and help

General emergency phone number: 112
Campus emergency phone number: +31-40-2472222
Campus reception phone number: +31-40-2479111 If you need other help please call Steinar Wouters or Edgar Vredenbregt.

Conference venue

The conference is held in the Auditorium of Eindhoven University of Technology. Talks are in lecture hall 4 (ground floor); refreshments, lunch and posters in the main hall (first floor). The Auditorium is located in the south-western part of the university campus (TU/e Science Park), within walking distance from Eindhoven railway station. The address is Groene Loper 1, Eindhoven.

Reception

Sunday night's reception is held in Grand Café De Zwarte Doos, located on the south-west corner of the university campus.

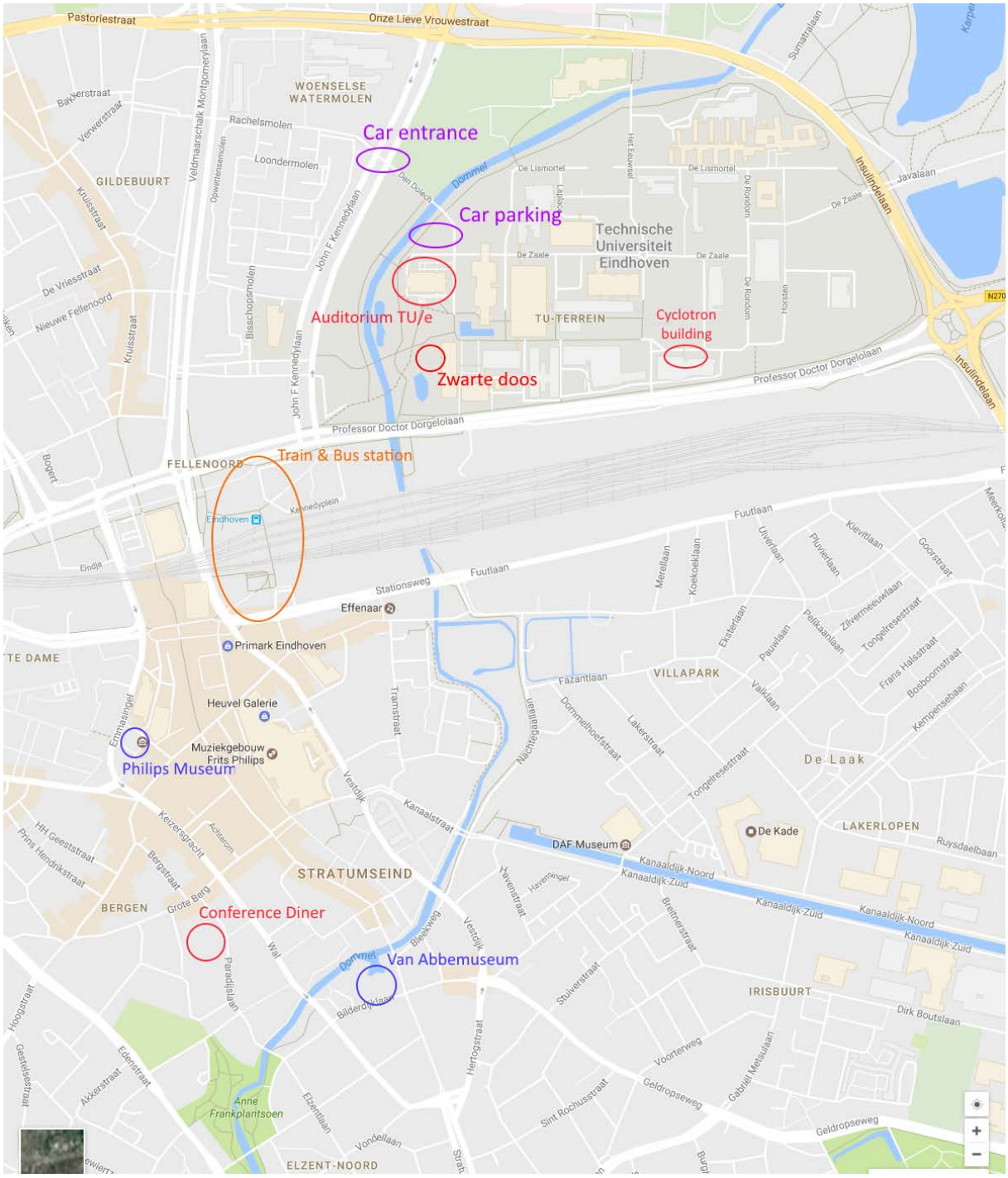
Conference dinner

The conference dinner is in restaurant "De Kazerne", address Paradijslaan 2, 5611 KN Eindhoven. Drinks are served from 18:00, dinner starts at 19:00.

CQT lab tour

A tour of the Coherence and Quantum Technology (CQT) lab is organised on Wednesday after the last session of talks. On-campus location is [Cyclotron building](), De Rondom 24.

Map of the center of Eindhoven



Internet access

There are two WiFi networks available for guests on the TU/e campus:

- Eduroam (secure; log on with your usual credentials)
- TUe-guest (not secure; free access)

Posters

The maximum format for posters is A0 in portrait orientation. Posters can remain on display from early Monday morning until after lunch on Wednesday. Attachment materials (Velcro stickers) will be provided.

Projectors

The aspect ratio of the projector in lecture hall 4 is 16:10. Both VGA and HDMI connections are available. You can connect your own device or use the default Windows desktop computer which accepts a USB thumb drive. If you need any conversion cables please provide them yourself.

Social program

On Tuesday afternoon the conference outing will take place in or near Eindhoven. All tours start from the Auditorium on the campus of TU/e. Choose from the following possibilities:

Cycling Tour to Nuenen (Van Gogh Village)

Cycling is a common mode of transportation in the Netherlands. People commute to work by bike and spend their free time in the woods and fields on their bikes. In this active outing we would like you to experience the same. We will gather at the conference location and hop on a bike to go to Nuenen, a neighboring village where famous painter Vincent van Gogh lived for some time. Here you can visit the Van Gogh church and tree and/or have a refreshment in the rustic village center. The tour ends at the conference location (Auditorium).

Van Abbe Museum of Modern Art

The Van Abbe museum is Eindhoven's museum of modern art. We will get (under guidance) a workshop in which the participants will focus on one thing: identify what they see in an artwork. The museum is renowned for its large collection of works by El Lissitzky, as well as works by, e.g., Picasso and Kandinsky.

Philips Museum

The Philips company shaped Eindhoven as a city and has its own museum in the city center, right at the location where Gerard Philips started out in 1891. You will be informed about Philips' and Eindhoven's history and can even look at the old incandescent light bulb factory where everything started. The permanent exhibition tells the story of how a small lamp manufacturer grew into a leading global company.

How to get here

Travelling by plane

Amsterdam Airport

The main airport of the Netherlands is Amsterdam Schiphol Airport. All major airlines fly to Schiphol. It has a direct connection by train to Eindhoven. The journey takes about one hour and 30 minutes, with trains running up to four times an hour. Eindhoven railway station is located in the heart of the city, within walking distance of the conference hotels and the conference venue. Taxis can be found at both ends of the railway station.

Eindhoven Airport

Eindhoven Airport is a regional airport with direct connections to destinations in Europe, including Dublin, London, Munich, Rome and Stockholm with low cost airlines

such as RyanAir and TUI. Eindhoven Airport is about 20 minutes from the city centre by bus or by taxi.

Other Airports
Eindhoven can also be reached by train from Brussels Airport in around three hours and from Düsseldorf Airport in about two hours.

Travelling by train

Eindhoven is part of the Dutch intercity network and has a direct rail connection with Amsterdam Airport. To plan your train trip inside the Netherlands, consult the Dutch railway planner.
The OV-chip card is the national public transport ticket system in the Netherlands and has replaced paper tickets. There are more card types for rail travel but most visitors use a single-use ticket. They carry a 1 Euro surcharge in addition to the standard fare. To validate the ticket, passengers must check-in and check-out using the card readers near the platforms or at the gate barriers.

Travelling by car

From all motorways around Eindhoven (A2, A50, A58, A67 and A270) signposts will indicate the direction Centrum, until Universiteit/ TU/e Science Park is indicated. There is ample, paid parking available at the Auditorium on campus. More information about parking can be found on the TU/e website. However, beware of restrictions due to construction on campus. During the conference you will probably not need your car for transport between the conference venue and hotel.

Cold atom ion sources

Jabez J. McClelland

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While most ion sources for focused ion beam (FIB) applications rely on a very sharp tip to create high brightness, a new type of source has recently emerged which instead exploits the extremely cold temperatures attainable through laser cooling [1]. In these sources, the brightness arises not from localizing the ion emission to a nanometer-scale area on the surface of a tip, but rather through a dramatic reduction in the random transverse motion of the ions. Here, neutral atoms are cooled to temperatures in the microkelvin range, ionized via near-threshold photoionization, and extracted with a uniform electric field to form a highly collimated ion beam. The cooling process, which does not involve any cryogens, is based on scattering of near-resonant laser light tuned just below a sharp absorption resonance in the neutral atom, and can attain temperatures as low as 10 μK in some species.

Particular advantages of a cold-atom ion source include access to new ionic species (laser cooling in over 27 atomic species has been demonstrated), a very low energy spread (permitting high resolution focusing at low beam energies), and a brightness that can be significantly higher than the industry standard liquid metal ion source (LMIS). Additional advantages include long term stability, insensitivity to contamination, and controllable emission current from several nanoamperes down to the single ion level.

Cold-atom ion sources have been realized so far with chromium [2], lithium [3], rubidium [4], and cesium [5,6]. A lithium ion microscope has been constructed using a magneto-optical trap ion source (MOTIS), and a number of applications have been demonstrated with this instrument. Low energy ion microscopy reveals new imaging modalities [7], lithiation of battery materials is studied on the nanoscale [8], and mode distributions in optical microdisk resonators are visualized with great detail [9].

With the introduction of this new type of source, a number of new applications will become possible. The additional selection of ionic species, together with an ability to achieve nanometer-scale resolution at low beam energy, will create opportunities to not only study nanoscale lithiation in battery materials, but also address more general questions about ion mobility in materials important for such applications as photovoltaics and next-generation electronic devices. The very high brightness and heavy atomic mass of Cs^+ sources will enable milling and FIB induced deposition with enhanced resolution, making possible, for example, circuit edit at the most recent, smallest nodes. These and other applications promise to make cold atom ion sources a significant addition to the already very capable family of FIB sources.

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[1] J.J. McClelland, A.V. Steele, B. Knuffman, K.A. Twedt, A. Schwarzkopf, and T.M. Wilson, Appl. Phys. Rev. **3** (2016), p. 011302.

[2] A. V. Steele, B. Knuffman, J.J. McClelland, and J. Orloff, J. Vac. Sci. Technol. B **28**, C6F1 (2010).

[3] B. Knuffman, A.V. Steele, J. Orloff, and J.J. McClelland, New J. Phys. **13** (2011), p. 103035.

[4] N. Debernardi, M.P. Reijnders, W.J. Engelen, T.T.J. Clevis, P.H.A. Mutsaers, O.J. Luiten, and E.J.D. Vredenbregt, J. Appl. Phys. **110** (2011), p. 024501

[5] B. Knuffman, A.V. Steele, and J.J. McClelland, J. Appl. Phys. **114** (2013), p. 044303.

[6] M. Viteau, M. Reveillard, L. Kime, B. Rasser, P. Sudraud, Y. Bruneau, G. Khalili, P. Pillet, D. Comparat, I. Guerri, A. Fioretti, D. Ciampini, M. Allegrini, and F. Fuso, Ultramicroscopy **164**, 70 (2016).

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[8] S. Takeuchi, W.R. McGehee, J.L. Schaefer, T.M. Wilson, K.A. Twedt, E.H. Chang, C.L. Soles, V.P Oleshko and J.J. McClelland, J. Electrochem. Soc., **163** (2016), p. A1010.

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ColdFIB – a FIB column with a laser cooled source

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In these last years, different ionic sources, like the GFIS, have been developed to go beyond the Gallium FIB ultimate resolution. Indeed, to improve FIB resolution performances, two development axes can be considered: optimize the optics, but we can't expect an important gain, or introduce new kind of ion sources.
The goal of courses of these new sources is to bring specifications which will help to fulfil a wide field of FIB applications. Among this application, it appears clearly that low energy performances become very important for FIB users and in this case the energy dispersion of the source is the main limiting factor. Furthermore, a source which has low energy dispersion will offer better resolution at higher energy (30kV).

In this objective we are developing a new source, based on a laser cooled cesium beam, that offer a really low divergence and energy dispersion and a two steps ionisation (Rydberg excitation + field ionisation) able to keep, as best as possible, this properties.
In this talk, I will present the coldFIB source and the dedicated column developed by Orsay Physics, I will discuss the principle of this source, the new results obtained and some first example of applications.

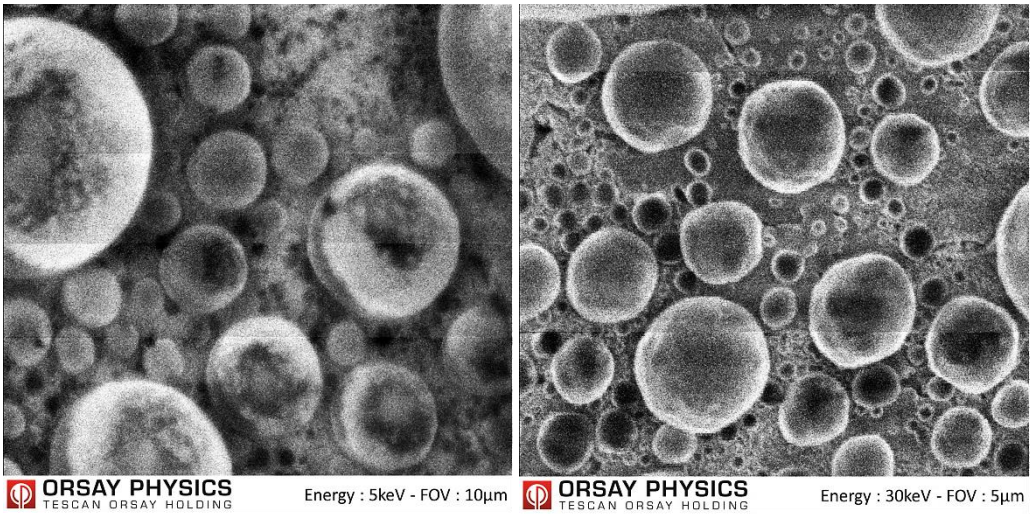

Figure 1: Tin on carbon sample: Example of images obtains with ColdFIB at 5keV and 30keV, with a different field of view, respectively 10 and 5µm.

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[1] L. Kime, et al., *High-flux monochromatic ion and electron beams based on laser-cooled atoms*, Phys. Rev. A 88, 033424 (2013)
[2] M. Viteau, et al., *Ion microscopy based on laser-cooled cesium atoms*, Ultramicroscopy (2016)

Towards a high resolution Rb^+ FIB

S. H. W. Wouters[1], G. ten Haaf[1], P. H. A. Mutsaers[1], and E. J. D. Vredenbregt[1]

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The atomic beam laser-cooled ion source (ABLIS) project [1] is aimed at creating an ultracold rubidium ion beam by the photo-ionisation of a laser-cooled and compressed thermal atomic beam. This ion beam will be used in a new focused ion beam (FIB) apparatus. Such systems are widely used in science and industry for sample inspection and manipulation at the nano-scale. Current gallium liquid metal ion source (LMIS) based FIBs can image and alter structures with a resolution down to 5 nm at a beam current of 1 pA and a beam energy of 30 keV. However, with the decrease in feature size achievable with photo-lithographic machines, the FIB spot size needs to shrink as well in order to keep circuit edit and repair viable. A smaller spot size in a FIB can be realised by increasing the ion beam brightness and/or by decreasing its longitudinal energy spread. The ABLIS project aims at creating an ion source that achieves both. In short, laser cooling and compression is applied to a thermal atomic beam of rubidium atoms to achieve the desired brightness. Then, two-step photo-ionisation in an electric field is applied to turn all atoms into ions while minimising heating due to Coulomb effects, thus preserving the brightness [2]. Keeping the ionisation volume small ensures that the longitudinal energy spread is minimised. Note that other research groups are working on ion sources based on similar ideas [3]. In this contribution an overview is given of the experimental realisation of the atomic beam laser-cooled ion source.

The performance of the laser cooling and compression were experimentally verified using laser-induced fluorescence [4]. The magnetic field gradient, cooling laser detuning and Knudsen source temperature were optimised to achieve the highest atomic beam brightness. Using these parameters the brightness of an ion beam with the same properties as the atomic beam, thus assuming all atoms can be ionised without heating, reads $(6^{+5}_{-2})\ 10^6$ A/(m^2 sr eV), an order of magnitude higher than the LMIS, and the flux is equivalent to $(0.6^{+0.3}_{-0.2})$ nA.

A high degree of ionisation is required in order to generate an ion beam with similar brightness as the atomic beam. Furthermore, to minimise the longidutinal energy spread that is introduced due to the electric field over the ionisation region, ionisation should take place in an as small as possible length. Calculations and simulations using the optical Bloch equations show that this is possible using a highly saturated ($s_0 > 10$) and focused excitation laser beam and an intense ionisation laser beam of at least 10^{10} W/m^2. To achieve this ionisation intensity over a region larger than the atomic beam diameter a build-up cavity was constructed that, when coupled to a commercial laser system, can achieve the desired intensity. Experiments were carried out to find the highest ionisation degree and to verify the simluations. For low currents an ionisation degree of roughly 80% was achieved. The maximum current that was extracted reads 0.6 nA.

Apart from the beam brightness, the longitudinal energy spread of the ion beam plays an important role in the formation of a small spot due to chromatic abberations in the electrostatic lens column. Here, a retarding field analyser was used to measure the energy spread. Preliminary results show that an energy spread as low as 0.25 eV FWHM can be achieved at beam energies ranging from 1 to 8 keV which is a significant improvement over the LMIS.

Currently, steps are taken to mount the ion source on a commercial FIB system. Once Rb^+ ion images can be obtained experiments will be carried out to achieve the smallest spot size and to measure the actual ion beam brightness by means of a waist-scan measurement.

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[1] S. H. W. Wouters *et al*, Phys. Rev. A **90**, 063817 (2014)
[2] G. ten Haaf *et al*, J. Appl. Phys. **116**, 244301 (2014)
[3] J. J. McClelland *et al*, Appl. Phys. Rev. **3**, 011302 (2016)
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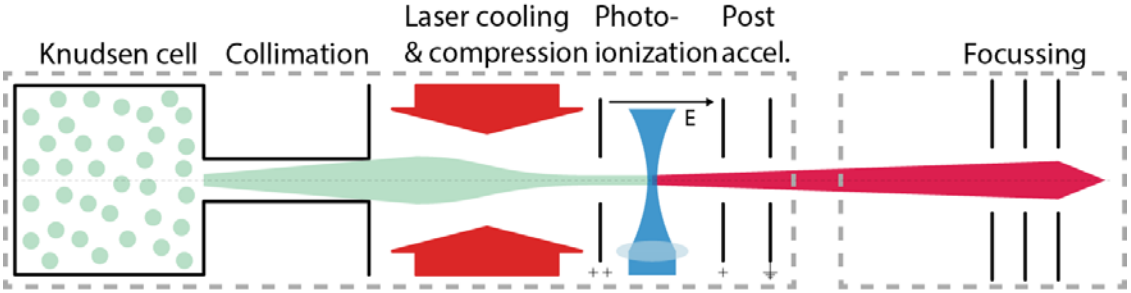

Cold atom electron sources

Rory Speirs, Dene Murphy, Dan Thompson, Joshua Torrance, Ben Sparkes,
Andy McCulloch and Robert Scholten
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The CAEIS cold-atom electron/ion source has achieved competitive nanoscale ion imaging [1] and offers unique properties for future application to ultrafast electron diffractive imaging [2,3]. Electron bunches produced by these sources have intrinsically high transverse coherence due to the very low source temperature, enabling single-shot high resolution diffraction [4]. Achieving practical imaging will require application of a diverse range of atomic physics. For example, optical excitation and ionisation allow generation of ultrafast bunches, but the bunch duration can vary by up to six orders of magnitude for relatively small changes in laser wavelength that enhance or inhibit specific photoexcitation pathways and below-threshold tunneling. Using streak methods, we have studied those pathways and demonstrated bunch durations of tens of picoseconds [5]. We have also explored two avenues for increasing brightness: using stimulated Raman adiabatic passage (STIRAP) [6] and selective field ionisation [7]. We are now developing a CAEIS designed for integration with a standard commercial focused ion beam column. The source will allow simultaneous extraction of both electrons and ions to enable correlated electron-ion imaging, and also production of heralded single ions using Rydberg blockade in the photoexcitation and ionisation volume.

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[1] J.J. McClelland *et al.*, Appl. Phys. Rev. **3** 011302 (2016).
[2] M.W. van Mourik *et al.* Struct. Dynam. **1** 034302 (2016).
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[4] R.W. Speirs *et al.*, J. Phys. B **48** 214002 (2015).
[5] R.W. Speirs, A.J. McCulloch, B.M. Sparkes, R.E. Scholten, N. J. Phys. (in press).
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[7] A.J. McCulloch *et al.*, Phys. Rev. A (*in press*).

The TU/e ultrafast and ultracold electron source

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We are developing an ultrafast and ultracold electron source based on near-threshold, femtosecond photoionization of laser-cooled and trapped rubidium gas. Recently, we demonstrated electron crystallography of graphite for the first time using the ultracold source [1]. The ultimate goal is ultrafast, single-shot electron crystallography of macro-molecules, which requires a high degree of control of the dense electron phase space distribution. The transverse phase space distribution has been extensively characterized in the past [2, 3, 4], resulting in electron temperatures as low as 10 K when using a femtosecond ionization scheme.
For characterizing the longitudinal phase space distribution we have developed a microwave cavity-based diagnostic element to correlate electron bunch lengths to streak images. This allows us to measure the pulse length with sub-picosecond temporal resolution. We show that we can make *both* ultracold *and* ultrafast electron pulses which have an rms pulse duration of 20 picoseconds [5]. These bunches are sufficiently short to be compressed to 100 fs bunch lengths using established RF compression techniques.
Additionally we have used a dedicated Wien filter to correlate bunch energy spreads to streak images. The simultaneous use of these diagnostic elements enables us to image the total longitudinal phase space distribution onto the detector, with both sub-ps time resolution and sub-eV energy resolution.
Finally we will discuss the status of our new compact ultracold electron experiment which is based on a grating magneto-optical-trap (GMOT), radio frequency acceleration and an ASI MediPix [6] electron detector.

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[1] Mourik *et al*, Struct. Dyn. **1** 034302 (2014)
[2] Engelen *et al*, Ultramicroscopy **136**, 73-80 (2013)
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[4] Engelen *et al*, Ultramicroscopy **147**, 61-69 (2014)
[5] Franssen *et al*, Struct. Dyn. **4** 044010 (2017)
[6] https://www.amscins.com

I6

Quantum degenerate electron beams

Herman Batelaan

University of Nebraska-Lincoln

Consider two electrons emitted from a source and travelling through free space to a detector that measures their arrival time. The electrons do not like to arrive together in time. This can be due to repulsive Coulomb forces between the electrons or Pauli forces. The latter is the Hanbury Brown and Twiss (HBT) anti-correlation in time, and it's observation is reported for free electrons [1]. This experiment was done with the highest degeneracy reported for free electrons: 10-4. The reason for the low value is that the experiment was done using a single-tip emission source that ran continuously and only rarely are two electrons emitted nearly simultaneously. The effect of Coulomb repulsion was not studied. Kodama has more recently published an analysis of the Tonomura group's original work on this problem and attributed its observed anti-correlation fully to repulsive Coulomb forces [2].

The overarching question is: "Can quantum degenerate electron beams be made?" We report on our theoretical [3] and experimental progress towards creating quantum degenerate free electron beams to add a new defining element to the emerging research field of free electron quantum optics.

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[2] Correlation in a coherent electron beam Tetsuji Kodama, Nobuyuki Osakabe, and Akira Tonomura, Phys. Rev. A 83, 063616 (2011)
[3] Quantum description and properties of electrons emitted from pulsed nanotip electron sources. P.Lougovski, H. Batelaan, Physical Review A 84, 023417 (2011)

Electrons and ions meet ultracold atoms

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Bringing together ultracold atoms and charged particles opens up new research directions in atomic physics. On the one hand, electrons and ions can be used to probe and manipulate ultracold atomic gases. On the other hand, a sample of ultracold atoms is an ideal starting point to generate ultracold electron and ion beams.
In this talk I will give two examples, how both research fields can benefit from each other. First, I will show that a focused electron beam can be used to image and manipulate ultracold quantum gases with high spatial resolution. To this end, we have adapted a scanning electron microscope for the study of ultracold quantum gases [1, 2]. Thereby, the imaging principle relies on the electron impact ionization of cold atoms with subsequent ion detection. The technique allows for in situ imaging of single atoms with a resolution of better than 150 nm. At the same time, the electron beam provides a precisely controlled source of dissipation which we exploit to observe quantum Zeno dynamics in many-body quantum system [3]. Secondly, I will present first results towards the generation of a high-repetition deterministic single ion source based on ultracold atoms.

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Atom Eyes:

„Scanning HElium atom Microscopy"

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Microscopy is an indispensable tool for the investigation of materials and surfaces. It has often been said that the whole field of Nanotechnology and Nanoscience began with the invention of Scanning Tunneling Microscopy (STM) and Scanning Force Microscopy (SFM). Recent years have also seen an immense development in particle probe microscopes, allowing atomic resolution in Transmission Electron Microscopy (TEM).

State of the art microscopy and imaging techniques are very powerful, in particular with respect to their high resolution, but there are some inherent challenging issues. Charged particle probe techniques like electron or ion microscopes as well as STM normally require the sample to be electrically conducting, whilst scanning probe techniques in general are rather slow and can only be used on quite flat samples and for small areas.

Recent years have shown big achievements in the field of scanning helium atom microscopy (SHeM) [1-5] enabling the development of a new type of matter wave microscopes which utilize neutral atoms as a probe beam.

The major advantage of the SHeM technique is that the neutral helium probe has a much lower beam-energy than other particle probe microscopes: less than 100meV for a de Broglie wavelength of less than 0.1nm. This energy is simply too low to cause any surface damage or penetration into solid material. At the same time the helium atoms are uncharged (neutral) and chemically inert. Thus, SHeM offers a completely non-destructive imaging technique that is equally suited to insulators, semiconductors, metals and delicate samples such as organic materials.

The few current existing SHeM microscopes are either based on a pinhole camera approach [2, 3] or use a focused helium beam concept [1,4,5]. Here I present the concept and advantages of the SHeM technique as well as the design of our focused NEutral helium beam MIcroscope NEMI, which we developed in Bergen. As one of the few existing instruments in the novel field of scanning helium microscopy, NEMI offers promising possibilities in its unique way of imaging with a focused neutral helium beam.

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Surface analysis of nanomaterials using a laser-cooled beam of spin-polarised metastable helium atoms

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Laser cooling presents an opportunity to manipulate neutral atoms with the precision and control enjoyed by techniques in charged particle and photon optics for decades. Previously, we have demonstrated how applying methods of laser cooling to collimate and focus a beam of metastable helium (2^3S) atoms can yield an ultra-high intensity probe for performing the extremely surface sensitive analysis technique of metastable de-excitation spectroscopy (MDS) [1,2]. A natural extension of a spectroscopic technique is to develop it into a microscopy to provide spatial information on the surface electronic, magnetic, and chemical properties of a material. Here, we describe the prospects of using laser cooling to generate an ultra-high intensity and nanometer-sized probe of helium atoms for microscopy and MDS applications.

Metastable-atom emission electron microscopy (MEEM) has been demonstrated using conventional He 2^3S sources on a number of occasions, firstly by Harada *et al*. who studied gold and ClAl-phthalocyanine (ClAlPc) monolayer islands grown on a graphite substrate [3]. The 5 μm resolution of the instrument was determined by detecting electrons from only a small area of the sample. The images of the islands were blurred due to aberrations caused by detecting electrons across a wide energy range (0-15 eV), and also because of surface diffusion. Yamamoto *et al.* produced energy-filtered MEEM images of a silicon oxide pattern on a Si(100) surface although the lateral resolution was poor at ~0.3 mm and a long 10 minute acquisition time was required [4]. More recently, Yamauchi *et al*. have reported the first demonstration of spin-polarized MEEM [5] which has potential applications for imaging, for example, the surface spin polarization of spintronic materials [6].

The electron imaging optics necessary to perform MEEM are identical to those used in PEEM systems. Electrons emitted due to He 2^3S de-excitation are typically accelerated to high energies (10 keV) to form an image using a cathode objective lens. Using an array of finely focused He (2^3S) probes, rather than this 'flood and image' approach, will result in the ejection of electrons from an area defined by the probe size. Modifying the electron optics of conventional MEEM apparatus will allow these individual signals to be combined to produce an image without the need for an aperture. Coupled with the high intensity associated with the focused helium nanoprobes, parallel acquisition will reduce the minutes long exposure times currently required to produce MEEM images.

One promising approach to producing an array of helium nanoprobes is to use a standing wave lens array (SWLA) such as that generated by counter-propagating laser beams in 2D. A dipole force is created that causes atoms to be attracted to the antinodes of the array by using laser light with a frequency detuned to the blue side of the He 2^3S_1—2^3P_2 transition (1083 nm). Using parameters typical for our experiment (longitudinal velocity of 1000 ms^{-1}), simulations show it is possible to tighly focus helium atoms as each antinode acts as a thick immersion lens. Even when broadening effects such as beam divergence and chromatic and spherical aberrations are considered, focal spot sizes in the nanometer range may be obtained.

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Circuit Edit Challenges and Ion Beam Requirements

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Circuit Edit (CE) is the discipline of modifying the internal routing in a chip, fixing errant functionality. Circuit edit is employed during the debug phase of prototype microprocessors, enabling quick validation of circuit modifications in lieu of lengthly mask refabrication and remanufacturing. Circuit Edit also provides working chips to enable progress on the extensive testing on these parts, enables debugging by "experimental surgery" on circuits not amenable to simulation, and enables probe pads for direct measurement and debugging of internal signals in the chip. All these capabilities directly impact the highly critical time to market of products of the Semi-Conductor Industry.

Focused ion beams (FIBs) based on Gallium liquid metal ion sources (LMIS) have been the mainstay of CE for many VLSI process manufacturing generations, spanning over two decades. The use of etchant gases for etch enhancement and selectivity, coupled with the use of precursor gases for deposition of FIB-induced dielectric and metal, make the FIB a complete, self contained tool for circuit modification. The live secondary electron (SE) image allows for monitoring and endpointing of the etching operations, especially effective due to the strong voltage contrast character of the FIB SE image. These FIBs have been characterized by versatility and robustness.

The perpetual size reduction of microprocessors features, driven by Moore's Law, has brought about evolutionary improvements over the years in repeated reductions of the probe size of these FIBs. Recently, however, the FIB industry has been squeezing the lemon on further improving Ga LMIS probe size. Another key attribute trending faster than feature size reduction, but which has only recently been recognized as a capability limitation is the signal to noise ratio (SNR) of the live SE image. This image constitutes the endpoint means of various CE steps, has been degrading due to the higher pixel density required for higher resolution imaging and growing aspect ratios. In contrast to the resolution improvement which scales linearly with the generational down-scaling of chip features, the SNR scales faster than the 1.5 power of the linear scaling. Both these trends form critical challenges to the CE discipline, and are forcing the adaption of new ion beam technology.

The talk will review the most challenging capability requirements of CE at the present and will address the future trends of these requirements. The attributes of a desirable ion beam for CE will be defined, and present knowledge on the suitability of various ion species and source technologies will be addressed.

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Low-energy and high-resolution ion beams from an applications viewpoint

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End users of commercial Focused Ion Beam (FIB) instruments are increasingly concerned with low-energy and high-resolution applications. Some examples include TEM lamella preparation, nanofabrication, circuit edit, and 3D volume analysis using FIB cross sectioning. In this presentation we examine some of the requirements and challenges of these processes. Special emphasis is given to "gas-assisted" FIB operations such as chemically-assisted etching and deposition, and the effect that the primary ion has on these processes. Emerging plasma-based FIB systems exhibit significant differences towards some of these applications, compared to traditional Ga^+-based FIB systems. Increasingly, the chemical nature of the primary ion matters. Some specific examples we consider include the electrical resistivity of deposited materials, the redeposition and accumulation of unwanted material during high-aspect ratio milling, the nucleation of droplets on the surface of III-V materials, direct-write surface modification for masking, and textural milling artifacts observed during FIB cross sectioning.

Quantum computer devices built from shallow implanted single atoms

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The new field of quantum technology is being driven by recent major initiatives including the Quantum Manifesto of the EU, the National Strategic Innovation Agenda of Australia with the aim of building a near-term quantum computer device, along with other initiatives worldwide.. We have developed methods to fabricate devices which exploit the internal quantum degrees of freedom of single atoms in the solid state. These devices bridge the foundations of modern information technology based on silicon into the future of ultra-scaled devices where quantum mechanics offers new functionalities for sensing, information storage, information processing and secure data transmission guaranteed by the laws of Physics. Here we focus on the development of a fabrication technique that employs shallow ion implantation, within 20 nm of the surface. This is is compatible with the process flow for the fabrication of single atom semiconductor devices with the standard tools of the industry where the implantation of swift ions into semiconductor materials has a long history and the semiconductor industry presently employs many implantation steps in the fabrication of a typical large scale integrated circuit. Our work with ion implanted phosphorus (^{31}P) atoms in isotopically pure silicon devices has driven a sequence of discoveries reporting exceptionally long coherence times for the ^{31}P nuclear spin quantum bit [1-5] with coherence times longer than 30 s [2]. To make the devices used for this work, a small number of ^{31}P atoms are implanted at 14 keV, range 20 nm, into a nano-scale construction site on an isotopically pure ^{28}Si substrate that is later surrounded by nanocircuitry for programming and read-out of the qubit. A significant near-term challenge in silicon is to fabricate deterministically implanted arrays of single atoms registered to control gates in a monolithic quantum device. This presentation shows how these challenges are being addressed [6] with near-term plans to halve the implant energy for shallower implants and improved precision from less straggling. In a recent development, it appears possible to extend these methods to engineer single colour centres in newly available device-grade diamond substrates. New device architectures in these materials based on deterministic implantation technology could form the building blocks of a future CMOS quantum computer fabricated with the standard tools of the semiconductor industry.

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FIB Platform Employing a Low-Temperature Ion Source

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We present a demonstration of a new high-performance ion source retrofitted to a commercial FIB platform. Spot sizes as small as (2.1 ± 0.2) nm (one standard deviation) are observed with a 10 keV, 1.0 pA beam. Brightness values as high as (2.4 ± 0.1) × 10^7 A m^{-2} sr^{-1} eV^{-1} are observed near 8 pA [1]. The measured peak brightness is over 24 times higher than the highest brightness observed in a Ga liquid metal ion source (LMIS); the spot size obtained by operating our source at 10kV is significantly smaller than the spot size achievable with the replaced LMIS operating at 40 kV.

The FIB platform utilizes a Low Temperature Ion Source (LoTIS). As previously described [2], this source is composed of a several discrete stages that collect, compress, cool and finally photoionize a cesium atomic beam. The beam transmits over 5×10^{10} atoms s^{-1}, which would be equivalent to an ion beam with over 8 nA if ionized completely. Extraction of currents up to 5 nA have been previously demonstrated.

We will present a description of the LoTIS-FIB system, together with an examination of the brightness and spot size measurement methodology; images acquired using the system will also be shown. Measurements of system performance at higher beam current will also be discussed.

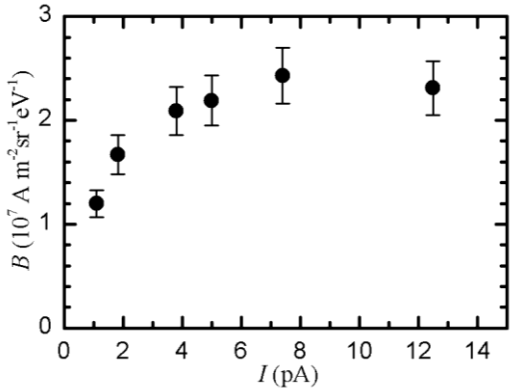

FIG 1. Brightness of the LoTIS from 1 to 13 pA. Brightness reductions at current below 4 pA are due to a limitations in the present system on the size of the ionization laser focal spot sizes.

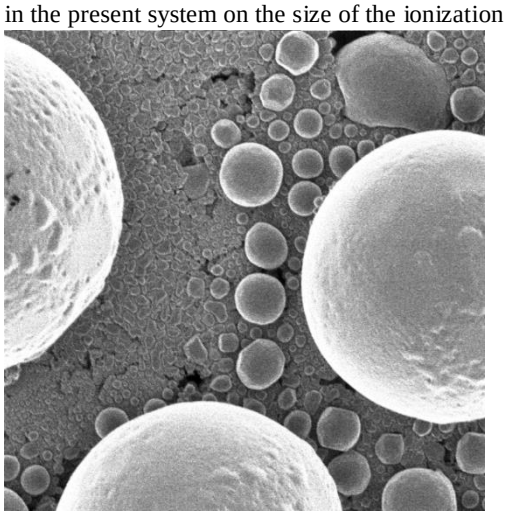

FIG 2. Image of tin spheres on carbon acquired with the Cs^+ LoTIS-FIB system. The field of view is 10 µm.

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Forced field ionization of Rydberg states for the production of monochromatic beams

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We study Rydberg ionization in an electric field in order to produce monochromatic ion and electron beams [1]. We will present an experimental study of the photoexcitation and ionization of high quantum defect states, using excitation from the $7s$ state in cesium to Rydberg states in the presence of a uniform electric field. Such states can exhibit complex ionization behavior, for instance, highly localized growth in the ionization rate due to interference effects. This indicates that large changes in the Rydberg ionization rate from small changes in electric field are possible when a nearly stable state crosses a more unstable state. A fast variation of the ionization rate with electric field allows for the production of beams with very low energy dispersion. We develop a simple two-level model to predict the voltage and spatial resolution that would occur when atoms are prepared in a state with such sharp ionization in electric field. This confirms that Rydberg forced ionization in an electric field presents a pathway for the production of high-brightness, highly monochromatic ion and electron beams.

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Disorder-Induced Heating in Ultracold Ion Beams

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The development of cold atom ion sources (CAIS) [1] is motivated by the desire to achieve sub-nanometre resolution [2] for the characterisation and fabrication of semiconductor devices, which would be an order of magnitude improvement over conventional ion sources (limited to 10 nm due to their inherently high temperature [3]). Unfortunately, the random arrangement of ions created under conventional CAIS ionisation conditions (Fig. 1a,b) leads to at least an order of magnitude increase in the ion temperature [4] and a corresponding decrease in source brightness. This effect is known as disorder-induced heating (DIH). The ability to suppress DIH by enforcing order into the system is therefore an important goal for the development of nanometre-precision milling and characterisation of semiconductor devices with a CAIS.

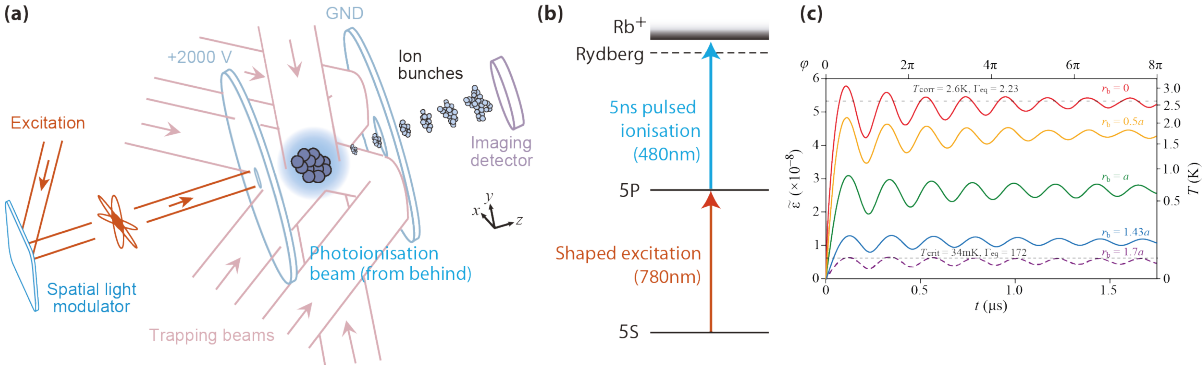

Figure 1: *(a) Cold atom electron and ion source (CAEIS) based on photo-ionisation of laser-cooled atoms; (b) two-colour photo-ionisation scheme used for conventional electron/ion bunch creation, which leads to disorder-induced heating; (c) An increase in spatial ordering, here quantified by r_b/a, where "a" is the average interparticle separation and r_b is the Rydberg blockade radius, leads to a reduction in electron/ion bunch temperature (T) and a corresponding reduction in bunch emittance (e) as the bunch evolves over time (t).*

Spatial order can be imposed on the ions by first exciting to Rydberg states, as interactions between the large dipole moments of Rydberg atoms shifts the energy levels of atom pairs so that only atoms spaced at greater than the blockade radius are excited. This phenomenon is known as Rydberg blockade [5]. An applied field then ionises those spatially correlated Rydberg atoms without affecting unexcited atoms. Here we present a theoretical model for the equilibrium coupling of an ion system with varying initial hard-sphere Rydberg blockade correlations and use it to quantify the suppression of disorder-induced heating in cold ion bunches due to the added order [6] (Fig. 1c). We also present experimental work demonstrating how coherent excitation to Rydberg states can be achieved efficiently using coherent excitation techniques [7].

In addition, as an alternate method for creating order, we theoretically quantify the disorder-induced heating in optical lattices with partial filling fractions, using a conservation of energy model involving the spatial correlations of the initial state and the equation of state in thermal equilibrium for a one-component plasma [8].

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Single ion microscopy

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I describe the deterministic source, which allows for delivering a single Ca^+ ion on demand and focus it into a spot of a few nm [1]. The microscopy of mask structures is one of the applications, where we employ the Bayes experimental design for maximum information gain [2]. In a second-generation setup, we will improve the spatial resolution to below 1nm and increase the rate of extracted ions by using fast shuttle operations [3] from a cold reservoir. We have started structuring solid state samples such as diamond with N_2^+ molecular ions to generate NV centers, rate-earth ions in YAG samples and will start implanting P^+ ions into ultrapure Silicium, to fabricate devices for quantum information processing [6].

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Helium Ion Microscopy:

High resolution Imaging and Nanomachining with He and Ne Ions

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The Helium Ion Microscope has been described as an impact technology offering new insights into the structure and function of nanomaterials. Combining a high brightness Gas Field Ion Source (GFIS) with unique sample interaction dynamics, the helium ion microscope provides images offering unique contrast and complementary information to existing charged particle imaging instruments such as the SEM and TEM. Formed by a single atom at the emitter tip, the helium probe can be focused to below 0.25nm offering the highest recorded resolution for secondary electron images. The small interaction volume between the helium beam and the sample also results in images with stunning surface detail.

Besides imaging, the helium ion beam can be used for fabricating nanostructures at the sub-10nm length scale. Researchers have used the helium ion beam for exposing resist and features as small as 4nm have been reported. The main advantage of helium ion lithography over electron beam lithography is the minimal proximity effect. The helium ion beam has also been used for deposition and etching in conjunction with appropriate chemistries. Helium induced deposition results in higher quality deposits than with Ga-FIB or EBID (Electron Beam Induced Deposition). Finally, the helium nad neao ion beams can be used for direct sputtering of different materials. Patterning of graphene has resulted in 5nm wide nanoribbons and 3.5nm holes in silicon nitride membranes have been demonstrated.

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Quantum electron microscopy – and a few words on photonics-based electron beam control

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Various fields of electron microscopy are limited by sample damage. For example, while transmissione electron microscopy of vitrified macro-molecular samples has recently arrived at a point that the samples can be reconstructed with atomic resolution ("cryo-EM"), several thousand copies of the same molecule are still needed to obtain this information [1]. The reason for this is that sample damage can so far not be avoided while attaining the required signa-to-noise ratio for such spectacular high resolution imaging.

In conventional electron microscopy, the probe electron interacts with the sample only once. We will show that a much more favorable scaling of the signel-to-noise vs. damage ratio can be obtained in other measurement setups, which can be shown to be quantum-optimal. We will discuss various realisations that are being pursued by the Quantum Electron Microscope Collaboration (MIT, Stanford, TU Delft and Erlangen) [2].

Electron resonators and ideally also coherent electron amplitude beam splitters (as oppoposed to wavefront beamsplitters) are required. We will discuss various realisations, in free-space but also with electrons guided by microwave fields. Based on the first Paul trap for electrons on a chip [3], we have recently demonstrated splitting of electron beams with the help of microwave fields, so far without showing the coherent nature of the process though [4]. Results of a highly coherent femtosecond laser-triggered electron source, as required for the generation of a well-controlled electron beam in space and time, will also be shown [5].

Last, electron acceleration with laser light at photonic structures – dielectric laser acceleration –will be briefly touched upon, and the current state of research presented. After the proof-of-concept experiment of dielectric laser acceleration in 2013 with relativistic [6] and non-relativistic electrons [7], we can now also deflect and focus the electron beam with optical forces only [8]. A sub-optical-cycle time-structure in the electron beam, enabling time-resolved experiments in the attosecond realm, has been achieved [9].

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Nano Aperture Ion Source

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Making brighter and more mono-chromatic ion beams is an obvious motivation for source development as this enables higher resolution in focused ion beam instruments. Even more driving is the desire for different ionic species. For efficient milling we like to use heavy ions, while for imaging, lighter elements minimize sample damage. Furthermore, preventing or employing chemical reactions can open up a variety of applications.

Ion production in the Nano Aperture Ion Source (NAIS) is based on electron impact gas ionization inside a sub-micron sized gas chamber. The gas chamber consists of two membranes of about 100 nm thick, which are separated by a distance of 100 nm to 1 µm. A small aperture of 100 to 500 nm in the membranes allows the ions to escape and a focused electron beam to enter the ionization region, while maintaining a high pressure inside the structure. The combination of a high current density electron beam and a highly confined ionization region makes excellent optical performance possible. The gas chamber can be filled with different gases such that a variety of ion species are available.

An important part of the recent efforts was devoted to understanding how the relevant physical processes determine the ion beam performance. The initial velocity and position distributions of the neutral gas particles, the ionization cross section, the electron current density, ion-neutral scattering, coulomb interactions and the electric fields around the double membrane structure are fundamental aspects of operation. These matters are studied by analytical models, numerical calculation, and ray tracing.

When using a higher particle density we obtain more ion current, but at the same time ion-neutral scattering sets in. An important finding is that the current and the brightness tend to keep increasing with increasing particle density, despite increasing ion-neutral scattering. A surprising result is that the spread in energies in the beam can be reduced as a consequence of more ion-neutral scattering.

Ion-to-ion Coulomb repulsion is found to pose a limit to the achievable brightness. The effect is relevant inside the chip, but also in the region where the beam is accelerated up to high voltage. Besides the direct ion-to-ion force, the surface induced charges in the membrane are found to have a relevant effect on the ion beam. The background electrons traveling along the ion beam give a negligible effect on the ion beam under nominal conditions.

The optical effects due to the electric fields, the ion-neutral scattering, and Coulomb interactions are studied simultaneously using Monte-Carlo ray tracing. In a realistic configuration, the simulations predict a brightness of about 3×10^6 A/m^{2}srV in combination with an energy spread of 1 eV.

An ion focusing and scanning column in combination with a knife-edge ion transmission detector was built for the purpose of measuring brightness. The setup was used to experimentally demonstrate a brightness of B = $1x\ 10^5$ A/m^{2}srV, which we consider a milestone result because it is already a competitive brightness when compared to a Ga LMIS while there is clearly room for improvement. We identify poor electron beam performance, too weak ion acceleration field, and too low ion lens voltage as improvable aspects. The measured brightness matches reasonably well with the simulated values for this sub-optimal configuration. Earlier energy spread measurements already indicated an obtainable spread of 1 eV [1].

Besides single charged ions, we expect multiple charged ions become constituents of the beam when using electron impact energies above the second ionization threshold. Rather surprisingly, a small amount of diatomic charged argon is predicted to become part of the beam. For a 1 keV electron beam we expect the beam to consist of about 88% single charged argon, 8% double charged argon, 2% triple charged argon, and 2% diatomic single charged argon.

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ElectroHydroDynamic emitters developments for improving Focused Ion Beam machines

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The The patterning of samples using Focused Ion Beams (FIB) is very popular, widely used both for industrial [1] and emerging nanoscience prototyping applications [2,3]. This FIB technique allows 3D and direct patterning of target materials using a finely focused pencil of ions having speeds of several hundreds of km/seconds at impact with a penetration range of a few tens of nanometre. Thanks to this, local information and/or modifications can be obtained at the target surface. As far as the ion nature is concerned, apart that many elements can be used in FIB technology as pure elements or in the form of alloys, gallium (Ga+ ions) is often preferred.
Traditionally for several decades FIB technology has been mainly based on gallium Liquid Metal Ion Sources (LMIS). LMIS are also known as electrohydrodynamically (EHD) driven ion emitters operating in a cone-jet mode. The very high brightness, long lifespan, small source size, and easy handling of this emitter remain its chief and most decisive advantages. On the other hand, some weaknesses are also well known that inhibit the resolution of EHD/LMIS-based FIBs. Therefore progress on ion sources operational characteristics still remains very desirable.
In this presentation we will first summarize our work aiming at understanding, optimizing and evaluating gallium LMIS “needle type” performances. In particular stable operation at lowest possible emission currents will be detailed. We will evaluate the gains in terms of patterning resolution and beam selectivity [4].There is firm evidence that progresses can still be expected from this mature technology.
We will then review and detail the advantages of Liquid Metal Alloy Ion Sources (LMAIS) that represent a promising alternative to expand the already remarkable application field and potential of FIB machines in the field of nanosciences. Indeed selecting the best suited elements transported in a focused ion beam can open new nanofabrication routes. In this presentation we will explain that nearly half of the elements of the periodic table can already be made available to the FIB technology as a result of a continuous research effort in this area [5] and how, in our opinion, nanofabrication shall now take benefit of these capabilities.
Finally we will introduce our new addition to the arsenal of EHD driven devices: The Ionic Liquid Ion Sources (ILIS). ILIS are capable to produce ion beams through field-evaporation, also in the cone-jet mode, but from room temperature molten-salts [6]. The possibility of extracting both positive and negative ions at emission current several orders of magnitude below LMIS standards is already a very appealing perspective in terms of virtual source size and brightness. Then we will show that ILIS allows to access new ionic species thanks to the almost limitless chemical engineering latitude of molten salts. Moreover subsequent tuning can be achieved via selecting the tip polarity, the ion emission current and the ion landing energy. We will show the possibility to achieve a new kind of FIB patterning using a beam of chemically reactive ion radicals native in the transported beam. This represents a formidable perspective for FIB technology.

In conclusion we will summarize our vision on the future of FIB technology based on electrohydrodynamically (EHD) driven emitters operating in the cone-jet mode, both in terms of performances, versatility and on the science frontiers these might help to push.

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SIMS analysis of advanced semiconductor materials and devices: present and emerging solutions.

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Reduced to its basic concept a transistor is composed of conductive regions (source/drain region) separated from the conduction channel by a p-n (or n-p) junction. In reality, the transistor device includes refinements targeting improved performance that require a complex dopant engineering scheme (halo implants, contact implants, Vt-adjust, ...) as well as the incorporation of alternative materials such as SiGe, Ge, and III-V. Such materials engineering has extensively been based on ion implantations and thermal (laser) treatments triggering extensive studies on the physics of ion implantation, deposition processes, dopant migration during annealing, defect formation etc. Such studies require material analysis techniques able to probe quantitively and reproducibly (< 1% errors) with very high sensitivity (< ppm) and high depth resolution (< 1 nm) the composition profiles of matrix elements as well as dopants atoms in complex multilayer systems. In particular the required sensitivity in combination with high depth resolution led to a unique dominance of Secondary Ion Mass Spectrometry (SIMS) for these applications. A careful selection of ion beam species, impact energy and angle of incidence allows to limit ion beam broadening effects and optimized ionization probabilities and thus high detection efficiencies.

Since SIMS is based on the interaction of an ion beam with the solid, spatial resolution has been limited to the achievable beam diameter (>200-500 nm), restricting its application to relatively large areas (test pads, > 20x20 μm^2). One of the advantages of such a "large" area analysis is the large number of atoms detected and analyzed (>10^{6-7}) such that ppm detection limits combined with nm depth resolution can be obtained. This will be demonstrated with a number of "standard" SIMS applications.

However extending SIMS towards next generation technologies which are completely 3D, required solutions that provide sufficient spatial resolution to deal with very confined volumes (<20 nm wide) as well as drastic signal enhancements to create statistically meaningful results. In a number of cases the topography of 3D-devices and the resulting non-uniform surface recession under ion erosion does add to the challenge of providing quantitative profiling in such structures.
This led to emerging concepts like

1. *1.5D SIMS* for the analysis of dopant conformality in Fin structures through interpretation of signal intensities in terms of side wall dose
2. *Compositional Microscopy* with SIMS by interpreting signal intensities of embedded systems into the dimensions of features
3. *Self-focusing SIMS* for compositional analysis in ultra-narrow trenches by selecting signals confined to the narrow region of interest

Ultimately the reduced dimensionality (a few nm^3) forced the introduction of Atom probe tomography (APT) which is an extremely powerful method providing composition and dopant analysis with excellent spatial and depth resolution (in many cases with the ability to resolve lattice planes and individual atoms) alloy composition analysis in small trenches, unexpected in diffusion in such volumes, dopant distribution and dopants decorating defects can in principle be identified

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Spectroscopy with the Low Energy Electron Microscope

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The Photo Electron Emission Microscope (PEEM) and Low Energy Electron Microscope (LEEM) started out primarily as imaging instruments, just like the Transmission Electron Microscope (TEM). In recent years, however, PEEM and LEEM while steadily improving imaging capabilities, have developed into powerful spectroscopic tools. While spatially-resolved Angle-Resolved Photo Electron Spectroscopy (ARPES) gives access to the occupied electron bands of a solid, Angle-Resolved Reflection Electron Spectroscopy (ARRES) reveals the unoccupied bands in 3D reciprocal space. Synchrotron-based core level spectroscopy gives chemical and magnetic information; surface plasmons can be seen with high time resolution with multi-photon laser-based PEEM, and with Electron Energy Loss Spectroscopy (EELS).
Diffraction-based techniques allow for real-space potentiometry, as well as detailed growth and strain studies. Thus, LEEM/PEEM instruments bring together high resolution microscopy and a broad range of spectroscopic tools that have never been combined in a single instrument before. I will review the state-of-the-art and outline directions for future developments, including the use of time-, spin- and highly energy- and momentum- resolved electron beams.

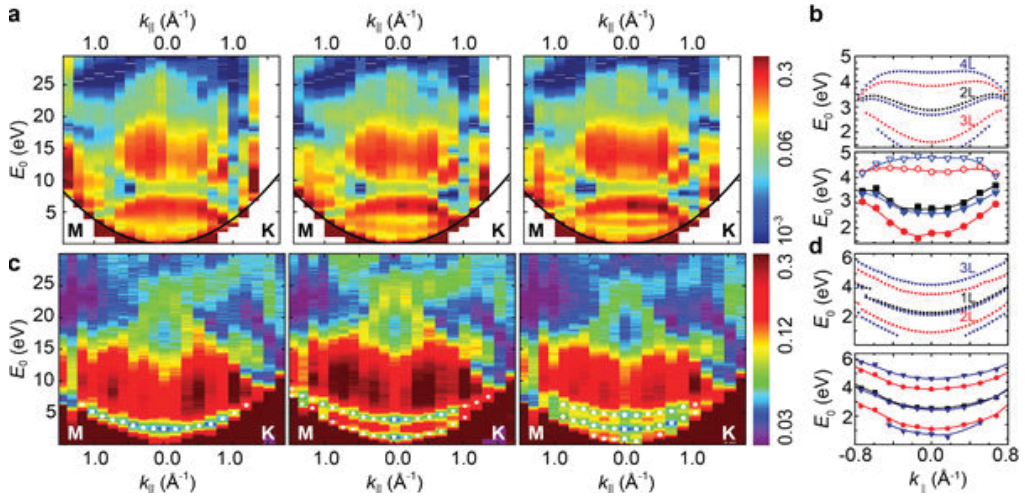

Figure 1. Angle Resolved Reflection Electron Spectroscopy (ARRES) is used to obtain information on the unoccupied electronic bandstructure of a solid. Top row (a): ARRES data on 2, 3, and 4 monolayers of hBN. (b) Comparison of theoretical (top) and experimental interlayer state dispersions for hBN. Bottom row (c): ARRES data on 2, 3, and 4 monolayers of graphene. (d) Comparison of theoretical (top) and experimental interlayer state dispersions for graphene. For detail see references (1) and (2)

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Low Energy Ion Scattering – analyzing the outer monolayer

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Low Energy Ion Scattering (LEIS) is a surface analytical technique known for its extreme surface sensitivity. The primary information gathered is the elemental composition of the outer atomic layer of a sample. In addition, the distribution of elements over the first few nm can be determined semi-quantitatively with single atomic layer resolution close to the surface.

For this purpose, ions with an energy of a 1 – 8 keV are scattered from the individual atoms in the surface. By analysing the energy spectrum of the ions scattered over a known angle the mass of the surface atoms can be determined. Quantification is straight forward as the intensity of the peaks in the spectrum is directly proportional to the surface coverage of the atoms the ions have scattered from.

In addition, scattering also takes place in deeper layers, leading to an additional energy loss of the scattered ions proportional to the depth. Due to different charge exchange mechanisms, this signal can be differentiated from the surface related signal, allowing – in addition to the surface analysis and without any sputtering – some insight into the in-depth distribution of the elements over the first few nm. This depth range can be expanded by sputtering the surface using a low energy ion beam.

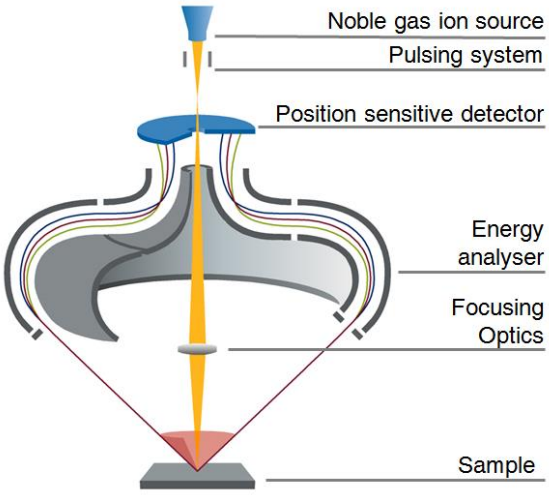

Fig. 1: Schematics of the Qtac analyzer

To make the unique properties of LEIS available to real-world samples, a dedicated analyser is required that offers sufficient sensitivity to restrict the analysis to a primary ion fluence that does not modify the outer layer significantly (static analysis). In addition, the angular and energy resolution have to be sufficient to separate all elemental combinations. The Qtac instrument is equipped with an analyser that uses a specific geometry and parallel detection to reach these goals. Two alternative noble gas ion sources and a low energy sputter source allow various analytical modes for practical surface analysis. This includes localized analysis with µm lateral resolution and a time-of-flight filtered mode that removes the secondary ion background from the spectrum, improving detection limits especially for light elements.

This contribution will explain in detail the technological and ion beam related aspects of LEIS. Examples of analytical applications are given from a variety of fields, including catalysis, fuel cells, semiconductors, and nano particles. In all cases, LEIS can deliver unique information to allow understanding materials, devices and processes.

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SIMS performed on the Helium Ion Microscope: new prospects for highest spatial resolution imaging and correlative microscopy

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The Helium Ion Microscope (HIM) has become an ideal tool for imaging and nano-patterning [1]. Imaging with helium ions leads to resolutions of 0.5 nm for secondary electron (SE) based imaging, while structures with sub 20 nm feature sizes may be rapidly patterned using Ne. Despite these advantages, the analysis capability of the instrument is currently limited. At beam energies of 35 keV helium or neon ions do not lead to the emission of characteristic X-rays from a sample. While some compositional information can be obtained from back scattered helium, identifying elemental information is more difficult.

In order to add nano-analytical capabilities to the HIM, we have developed a Secondary Ion Mass Spectrometry (SIMS) system specifically designed for the Zeiss ORION NanoFab HIM [2-4]. SIMS is based on the generation and identification of characteristic secondary ions by irradiation with a primary ion beam (in this case helium or neon). It is an extremely powerful technique for analysing surfaces owing in particular to its excellent sensitivity (detection limits down to the ppb are possible, so that SIMS can be used to detect both major and trace elements), high dynamic range (a same signal can be followed over several orders of magnitude), high mass resolution and ability to differentiate between isotopes.

In SIMS, the typical interaction volume between the impinging ion beam and the sample is around 10 nm in the lateral direction. As the probe size in the HIM is substantially smaller (both for He and Ne), the lateral resolution on the integrated HIM-SIMS is limited only by fundamental considerations and not, as is currently the case on commercial SIMS instruments, the probe size [4,5]. We have demonstrated that our instrument is capable of producing elemental SIMS maps with lateral resolutions down to 12 nm [4-6] (see as an example Figure 1 showing Co distributions obtained from a WC-Co sample with 10 µm and 3 µm fields of view). Furthermore, HIM-SIMS opens the way for in-situ correlative imaging combining high resolution SE images with elemental and isotopic ratio maps from SIMS [4,5]. This approach allows SE images of exactly the same zone analysed with SIMS to be acquired easily and rapidly, followed by a fusion between the SE and SIMS data sets.

We will present the performance characteristics of the HIM-SIMS instrument along with the latest results in the field of materials science.

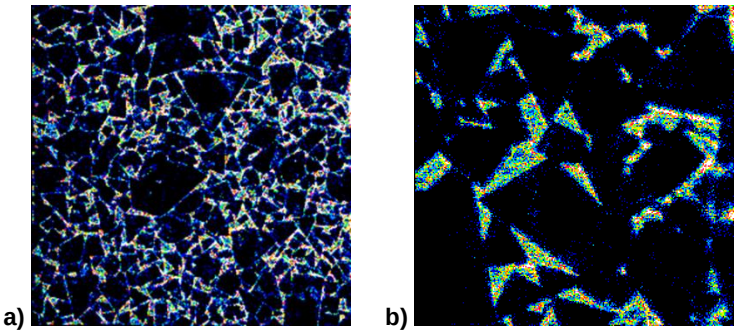

Figure 1: Secondary ion images of Co^+ from a WC-Co sample for a field of view of a) 10 µm and b) 3 µm.

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Ultrafast Transmission Electron Microscopy with Laser-triggered Field Emitters

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Ultrafast Transmission Electron Microscopy (UTEM) is an emerging technique to study structural and electronic dynamics on the nanoscale [1]. Besides its use as an analytical tool with simultaneous femtosecond temporal and nanometer spatial resolution [2], UTEM also provides for a unique test bench to study interactions of electron beams with optical near-fields [3-7], including the quantum coherent manipulation of free-electron states [4,6-7].
This talk will discuss the development and present status of the Göttingen UTEM initiative, giving several examples of our recent work. The developed UTEM operates based on laser-triggered photoelectron emission from nanoscale field-emitter cathodes, which enables experiments with a temporal resolution down to 200 fs, a nanometer beam focus, and an energy resolution of 0.6 eV. Using this instrument, we are presently pursuing a variety of applications in nanoscale structural, electronic and spin dynamics, such as Ultrafast Lorentz Microscopy for the study of magnetization dynamics and Ultrafast Convergent Beam Electron Diffraction (UCBED) to quantitatively access local structural dynamics.
Another focus point of our investigations has been the study of quantum coherent phenomena in free-electron beams interacting with optical near-fields at nanostructures. Specifically, for swift electrons traversing intense optical near-fields [3-7], we observe multilevel Rabi-oscillations on a ladder of quantized free-electron states [6], and implement Ramsey-type dual interactions in polarization-controlled, spatially separated near-fields [7]. Employing phase-locked two-color fields, coherent control of free-electron states is demonstrated [8]. We introduce a scheme to characterize the quantum state of such phase-modulated free-electron states in terms of their density matrix or Wigner function [8]. Finally, we demonstrate various new possibilities in the coherent manipulation of the longitudinal and transverse degrees of freedom of electron wave functions, including the preparation of attosecond electron pulses for optically phase-resolved electron microscopy.

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Sub-10 fs relativistic electron beams with ultralow emittance for ultrafast electron diffraction

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Velocity bunching allows to achieve ultrashort bunch lengths ultimately limited by space charge and longitudinal emittance effects. The scheme works by imparting a negative longitudinal position-velocity correlation is established (typically via an rf cavity), which then results after a dispersive section (which for low energy particle can be just a drift) in a tight longitudinal focus.

Velocity bunching is most effective for low energy electrons (keV) [1], but can be performed on meter scales with electron beams of a few MeV. In this paper, we describe an experiment where we obtained extremely small transverse and longitudinal emittance bunches in an RF photogun, allowing longitudinal bunch compression down to 7 fs rms. Advanced beam diagnostics are essential to characterize these beams. In particular we show that RF streak cavities are well suited to measure ultrashort bunches produced via velocity bunching even when the bunch size varies significantly within the measurement region provided that the waist is non laminar.

With electron bunches shorter than 10 fs, the largest contribution to the temporal resolution in ultrafast electron scattering techniques will be the jitter in the relative time-of-arrival of the laser and electron beam. Development of high resolution time stamping technique to temporally sort the date with the required resolution is therefore the next frontier in ultrafast electron diffraction. We present our approach based on THz-based electron streaking. This work represents a crucial step in the characterization of ultrafast electron beams as well as open the door to the visualization of the fastest configurational changes in solid state and gas phase systems.

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Electron microscopy of electromagnetic waveforms

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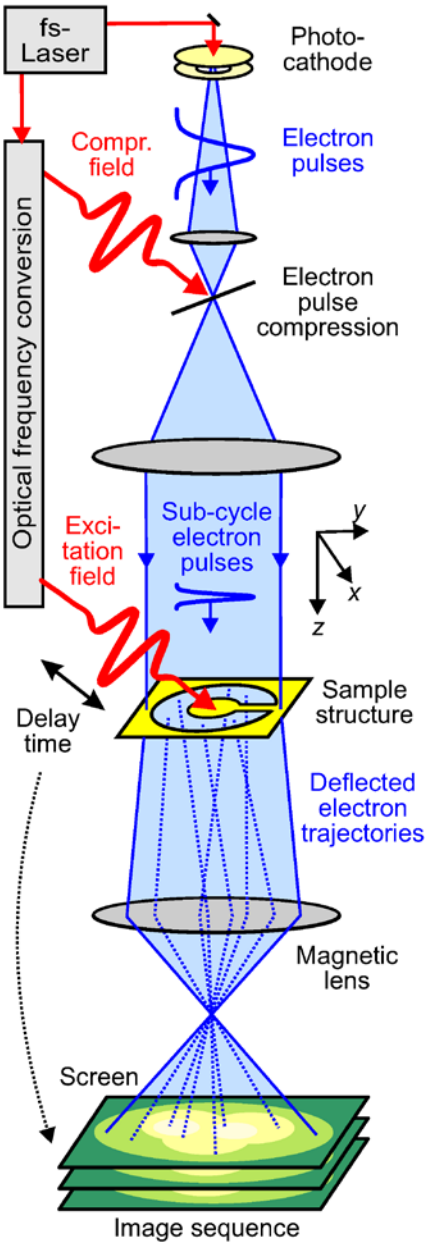
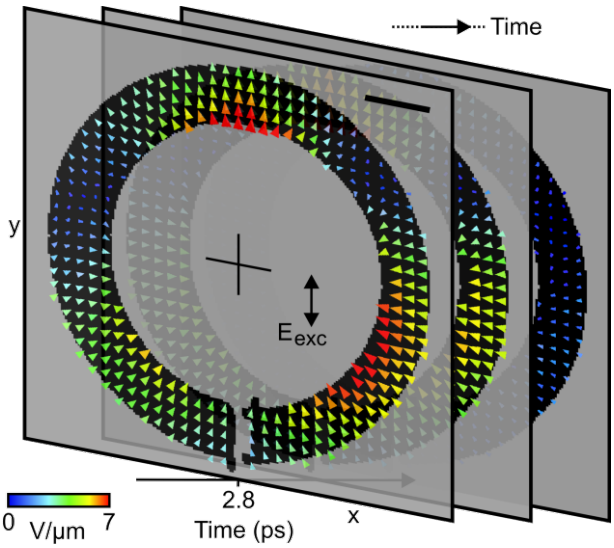


Electron microscopy works at a 100,000× smaller wavelength than light and therefore allows studying matter and materials with subatomic resolution. Rather elusive for electron microscopy, however, have been electrodynamic phenomena, although oscillating currents and fields are fundamental to the operation of almost any information processing device or metamaterial.

Here we report a merger of the electron microscope's supremacy in matter characterizations with a sub-cycle and sub-wavelength access to electromagnetic phenomena [1]. Femtosecond electron pulses (blue) are generated by pulsed-laser photoemission and further compressed in time by an optical field (red). The beam passes through the sample, here a slit-ring resonator that is excited with a single-cycle, phase-locked electromagnetic pulse (red). The time-compressed electron pulses [2] are ~15 times shorter than the excitation half-cycle, and therefore the fields at the sample are frozen in time for the electrons passing by. Hence, there is a local beam deflection that is proportional to the instantaneous electromagnetic field vectors via the quasi-classical Lorentz force. A pump-probe sequence therefore produces a movie of the electromagnetic field vectors in the sample (see below).



In principle, any light-matter interaction starts with atomic-scale charge displacements, and waveform electron microscopy or diffraction at subatomic resolution could potentially reveal those motions. More straightforward, however, will be studies of collective carrier dynamics and field effects in nanoscale devices, for example in electronics, metamaterials, nanophotonic circuitry, near-field sensors, or light-harvesting nanostructures. That waveform imaging and shape characterization now require only one instrument—the electron microscope—will likely be advantageous for such investigations [1].

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Ultra-High Brightness Electron Beams From Very-High Field Cryogenic Radiofrequency Photocathode Sources

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Recent investigations of RF copper structures operated at cryogenic temperatures performed by a SLAC-UCLA collaboration have shown a dramatic increase in the feasible maximum surface electric field, up to 500 MV/m. We examine use of this frontier development to enable a new generation of cryogenic photoinjectors that may attain, through enhancement of the photocathode launch field by a factor of 4, one-to-two orders of magnitude increase in peak electron beam brightness. We present detailed studies of the beam dynamics associated with such a system. In cases relevant to LCLS-like hard X-ray FELs case, we use start-to-end simulations showing that the high brightness and low emittance of this source enables operation of a powerful hard X-ray FEL reaching a photon energy of 80 keV. The preservation of beam brightness using in compression is discussed. Also, extreme low emittance scenarios obtained at low operating charge, appropriate for dramatically pushing performance limits of ultrafast electron diffraction and microscopy experiments, are reviewed. While much of the gain in brightness is due to increase of the emission current density via field enhancement, further increases in brightness due to lowering of the intrinsic cathode emittance in cryogenic operation are also enabled. The potential to probe fundamental brightness limits in these cold, dense beam systems is examined. Issues in experimental implementation, including: dark current suppression, cavity optimization for lower cryogenic thermal dissipation, external coupling, and cryo-cooler systems are discussed.

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O1

A Low-Energy Antiproton Beamline for ALPHA-g

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The ALPHA experiment at CERN uses a magnetic minimum trap to confine small populations of antihydrogen atoms, produced by gradually merging cold plasmas of antiprotons and positrons. Precision measurements with trapped anti-atoms can provide a unique probe of fundamental symmetries such as the CPT theorem and weak equivalence principle, and could help to explain why antimatter is so scarce in our universe. While recent work with the ALPHA apparatus has been highly successful in measuring the spectrum [1] and charge neutrality [2] of antihydrogen, there is now a growing interest in direct tests of antimatter's gravitational behaviour. As such, the ALPHA apparatus will be expanded in 2018 to incorporate a second, vertical atom trap for the first direct precision measurements of antimatter gravitation.

In the existing ALPHA apparatus, a typical trapping cycle will only yield around a dozen trapped anti-atoms due to the shallow depth of the magnetic minimum trap ($\sim 0.54\,\mathrm{K}$). In this respect, the efficient extraction and tranport of low-energy ($50\,\mathrm{eV}$) charged plasmas into the new atom trap will be critical towards achieving favourable experimental conditions with large numbers of trapped anti-atoms. However, as positrons and antiprotons are initially stored and cooled in Penning-Malmberg traps with strong axial magnetic fields ($0.15\,\mathrm{T}$ and $3\,\mathrm{T}$ respectively) the controlled transport of extracted beams can present a number of challenges. For instance, heavy particles such as antiprotons can begin to move non-adiabatically in regions with weak magnetic fields, leading to magnetic mirroring where the beam is later injected back into a separate particle trap. In this regime, it is critical that the magnetic moment of the beam is minimised during transport to prevent losses due to magnetic mirroring at the point of re-injection.

This work details the recent design and simulation of magnetic beamlines for charged particle transport throughout the expanded ALPHA apparatus.

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O2

Time-of-flight microscopy implementation for the study of cold electron beam

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Photoionization dynamics of magneto-optically trapped (MOT) Cs atoms was studied with help of time-of-flight microscope to estimate the suitability of such kind of sources for generation of fast electrons with very narrow energy spread. A momentum-microscope-like setup with a delay-line detector (DLD) gives an apportunity to detect simultaneously time and spatial coordinates of photoelectrons, namely transversal coordinates x and y and time-of-flight τ [1]. Such experiment provides direct observation of the ejection dynamics, which is crucial for understanding the factors limiting the cold electron source. Spatio-temporal distributions are studied as a function of the electric and magnetic fields and the initial kinetic energy of the photoelectrons. The measured patterns are unexpectedly complex, due to the Lorentz force inducing spiral trajectories.

The measurements were done for electron bunches with different initial kinetic energies of 0 up to 50 meV (variable) and 860 meV. For the ionization, the transverse mode was used when ionization laser (Ti-sapphire laser of 750-850 nm or pulsed blue laser of 375 nm) is perpendicular to the electron beam (axis of the optical system). Experimental results show that the increase of initial kinetic energy leads to beam widening and increased time spread between electrons with different emission angle θ that significantly increases up to E_{kin}=25 meV. Then the pattern becomes more complicated and for bunches with E_{kin}=860 meV, in case of presence of the magnetic field gradient, the trajectories of electrons with $\theta > 60°$ are spirals. The calculations reveal a 1:1 correspondence with the experimental results. From theory and experiment it is clear that the dependence on photon energy reflects the increase of transversal momentum. The signal becomes wider in the direction perpendicular to the optical axis. The time spread induced by the electric field gradient in the ionization volume is 1 ns. The time spread between electrons with $\theta = 0$ and 180° (that move the positive and negative z-axis) is only 430 ps in case of very low initial kinetic energy value of E_{kin}=1 meV. Full signal width is 40 and 12.5 ns for the blue and Ti-saphire lasers correspondingly [2].

In order to use the MOT as pulsed monochromatic cold electron source, two improvements seem essential: an additional aperture for restricting the accepted emission angles (thereby decreasing the time spread) and/or magnetic field switching. Switching, along with accurate synchronization with the ionization laser pulses helps to make the trajectories simplier and to decrease the time spread. The first results with pulsing of the magnetic field will be presented.

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Faraday waves in Bose-Einstein condensates

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Degenerate Bose gases allow for the study of matter-wave interference in atoms. Elementary excitations such as dipole and quadrupole modes have initially been observed, and are well-described by theory. In a cigar-shaped Bose-condensed gas higher-order axial patterns, the Faraday modes, are observed [1]. In our experiment we perturb the condensate with a single kick in the radial direction. The radial mode couples through non-linear interactions to the Faraday mode. Experiments show that the Faraday pattern appears, disappears and reappears. To describe this behavior we study the system both theoretically and numerically. The mode functions derived from theory match simulation and experiment. The coupling strengths are strongly peaked and Bose-enhancement of the coupling to modes ensures the excitation of a single Faraday mode. We compare theory, simulation and experiment, and provide insight in the reappearance of the pattern.

Figure: Experimental observation of Faraday pattern in a Bose-Einstein condensate. [2]

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O4

Multi-pass transmission electron microscopy as a tool for structural biology

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The number of biological macromolecules with a solved structure increases dramatically each year. This development is being driven by the technique of cryogenic-electron microscopy (cryo-EM) which saw great technological advances over the last few years [1]. For all the strengths of modern cryo-EM, many small and weakly scattering protein structures remain out of reach, as the achievable resolution is limited by the electron dose that can be applied without causing significant damage to the structure itself. Modern cryo-EM is operating close to this classical limit [1].

Improved sensitivity and spatial resolution will thus rely on fundamental advances in the cryo-EM method. Most protein structures represent weak phase objects that change the phase of an electron wave, but not its amplitude. Studies from the quantum metrology community show that one can go beyond shot-noise limited phase measurements [2]. One approach is to pass each probe particle through the specimen multiple times. This represents an approach that is optimal in terms of sensitivity and damage reduction [2].

We have recently demonstrated this concept experimentally in optical microscopy [3]. Here we discuss its applicability to cryo-EM. Our simulations [4] show that multi-pass TEM allows for a tenfold damage reduction in imaging small proteins. We also present a design study that shows that it is feasible to construct a multi-pass TEM. Knowing the structure of proteins is crucial for understanding diseases like Alzheimer or Parkinson. Multi-pass microscopy can enable protein structure determination by enhancing the sensitivity of electron microscopy to beyond the classical limit.

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O5

A novel method for time-resolved electron energy loss spectroscopy using microwave cavities

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At the Eindhoven University of Technology, the use of microwave cavities for the creation of a high brightness pulsed electron beam is being investigated. Currently, a novel method for time-resolved electron energy loss spectroscopy (TR-EELS) is being developed that makes use of these high brightness pulses.
TR-EELS is a technique that can be used to investigate the structural dynamics of a wide variety of samples. However, to reach energy resolutions below 100 meV, conventional methods impose strict requirements on the average current and beam quality, which are very difficult to meet using a pulsed electron beam. Therefore, it is proposed in this talk to use the time-dependent electric field of a TM_{010} microwave cavity as a longitudinal lens, allowing for very precise imaging of the velocity distribution acquired by the electrons after interaction with a sample. This technique nicely demonstrates the versatility of microwave cavities as longitudinal phase-space manipulators, and provide a viable alternative to current techniques.
The setup proposed in this talk uses a 30 kV SEM, and a distance of two meters over which two TM_{010} and two TM_{110} cavities are placed. From simulations, the minimum energy resolution reachable in this setup is found to be 22 meV, combined with a temporal resolution of 3 ps. The use of the TM_{110} cavities has already been demonstrated [1], and some preliminary measurements on the addition of the TM_{010} cavities have been done. Adding further improvements to the setup could open up the way to few meV measurements with high-energy pulsed electron beams. Combined with diffraction techniques, this would allow for the detection of the dispersion curves of short-lived many-body structural and electronic excitations close to the Fermi level.

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O6

Creating ultrafast electron pulses using a microfabricated laser-triggered Beam Blanker

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Ultrafast electron pulses enable imaging of transient dynamics with nanometer and femtosecond resolution. Such pulses are typically created by illuminating a flat photocathode or a cold-field emitter with femtosecond laser pulses. [1,2] Using a cold field emitter, an ultrafast Scanning Electron Microscope (USEM) has been realized enabling to image charge carrier diffusion in time and spatial domain. [3] Another approach to achieve ultrafast electron pulses is to use beam blankers using GHz magnetic or electric fields with resonant cavities, hence such blankers are relatively large. [4,5]

Recently, we presented the concept of a laser-triggered beam blanker for use in regular EMs that allows easy and quick switching between continuous-beam and ultrafast modes of operation. In this concept we propose to use a micro fabricated beam blanker controlled by a photoconductive switch, which is illuminated with femtosecond laser pulses.

Here, we will present a detailed theoretical and numerical analysis of the performance of such a beam blanker in terms of pulse duration and (induced) energy dispersion. Using COMSOL simulations we show that our design can deliver sub 100 fs electron pulses. Several designs are discussed for such a system and their effect on the energy spread of the electron beam. We show that such a system can also be easily used as an electron pulse compressor that can operate at low energy laser pulses. We will also discuss the performance enhancement of the Auston switch using plasmonic contact electrodes. [6]

We fabricated and integrated the beam blanker and a LT-GaAs photoconductive switch in one micrometer scale device, this enables us to deflect the beam at ultrafast time scales. We did fabricate the ultrafast beam blanker on a LT-GaAs chip. Also we designed a stick containing the blanker into the beam line of a commercial Quanta FEG SEM. Finally we will present our progress towards experimental realization and characterization of an ultrafast beam blanker, showing laser-triggered electron beam deflection.

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O7

Ultrafast Time-resolved Electron Microscopy using microwave cavities

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We are studying the possibility of using a microwave TM_{110} streak cavity in combination with a slit to chop a continuous electron beam into ultrashort electron pulses. We have shown in theory, simulation and experiment that this can be done with minimal increase in transverse emittance and longitudinal energy spread.

The cavity can create pulses at a repetition rate of 3 GHz, but by driving the two orthogonal cavity modes independently, we can reduce this to 75 MHz. When synchronized to a mode-locked laser system, this should allow for high-frequency pump-probe experiments with the spatial resolution of high-end electron microscopes, combined with 100 fs temporal resolution, and without the need for amplified laser systems.

At Eindhoven University of Technology we have inserted such a cavity in a 200 kV FEI Tecnai microscope. We have measured 1 ps electron pulses, accurately synchronized to our Ti:Sapph oscillator, with only 10 W of input power. Furthermore, we have measured that the transverse emittance and energy spread of our original TEM beam are fully maintained. We are now working towards our first pump-probe experiment.

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Single ion source with tunable rate based on ultracold atoms

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An ion source with minimal energy spread and deterministic emission has many applications in basic research and technical applications including surface spectroscopy, ion implantation or ion interferometry.
We have developed an ion source based on ^{87}Rb atoms confined in a magneto-optical trap. The atoms are ionized with a three photon scheme, built-up of infrared lasers. This results in a minimal energy transfer to the ionization fragments and reduces the electron background from the photoelectric effect.
To detect the electrons and ions, we currently use channel electron multipliers (CEM). The electron, registered within a few ns after ionization, is utilized for the deterministic operation of the ion source. The much slower ions are controlled by a gate electrode, which is by default blocking them. If an electron is registered, the gate is opened for a short time to let the corresponding ion pass.
Currently, we are able to operate the source with an ion rate from a few to 10^4 s^{-1} in gated mode, and 10^6 s^{-1} without gate operation.
In a next step, the ion CEM will be replaced with a position sensitive detector for ion momentum spectrocopy. Additionally, an adaptive ion optics upgrade may be used to manipulate ion trajectories in real time and allow for aberation corrections.

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Compact Ion Sources Based on Surface-Patterned Atom Chips

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Charged particle sources based upon laser cooled atoms are beginning to be used in a variety of applications from ion implantation [1] to single-shot electron diffraction [2]. However, in general, cold atom apparatuses require intricate laser systems and large-scale vacuum chambers, making them bulky and expensive. Here we report on progress towards a compact and inexpensive apparatus for cold charged particle production. The source is based upon a Magneto-optical trap that uses a surface-patterned diffraction grating providing single-beam laser cooling [3]. The photoionisation is achieved using all infra-red diode lasers which are cheaper and more compact than the usual frequency-doubled alternatives [4].

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Electron Temperature Control in Ultra-cold Neutral Plasmas and Electron Temperature Measurements in Rydberg Plasmas

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We report on the results of experiments that have been carried out at Colby College over the past few years on ultra-cold neutral plasmas (UNPs) made from cold Rb atoms in a magneto-optical trap (MOT). Specifically, we have investigated the effect of Rydberg atoms embedded into the UNP on the plasma electron temperature, and have observed both heating and cooling of the plasma. Additionally, we have measured the expansion velocities of UNPs which evolve from samples of cold Rydberg atoms ("Rydberg plasmas") and obtained values for the effective electron temperature in such plasmas.

Electron temperature control of a UNP using Rydberg atoms We have experimentally demonstrated a mechanism for controlling the expansion rate of an ultra-cold neutral plasma so that it is different from the value determined by the photo-ionizing laser frequency. We achieved this by adding Rydberg atoms to the UNP 10 - 20 ns after its creation, a technique that was first proposed in [1]. Specifically, we added $nd_{5/2}$ state atoms with $n = 24 - 60$ to UNPs with initial electron temperatures, $T_{e,0}$, in the range 10 - 250 K. The evidence is both indirect, from the change in the electron evaporation rate from the UNP, and direct, from the change in the asymptotic plasma expansion velocity, v_0, measured using the time-of-flight (TOF) spectrum of Rb^+ ions. The "crossover" between heating and cooling occurs when the binding energy of the embedded Rydberg state is $E_b \approx 2.3 \times k_B T_{e,0}$. This result strongly supports the existence of a "bottleneck" in the state distribution of Rydberg atoms formed by three body recombination (TBR) [2]. Finally, we show that the amount of heating or cooling is linear in the number density of Rydberg atoms added to the UNP for small Rydberg densities, but saturates at higher densities to a temperature that is determined solely by the Rydberg binding energy. These results are in good general agreement with Monte-Carlo calculations.

Measurement of electron temperatures in ultra-cold Rydberg plasmas We have measured the asymptotic expansion velocities of ultra-cold plasmas (UNPs) which evolve from cold, dense, samples of Rydberg rubidium atoms using ion time-of-flight spectroscopy. We create dense samples of nd Rydberg atoms ($n = 24 - 110$, $\rho = 10^7 - 10^9$ cm^{-3}) using a narrow-bandwidth pulsed laser system. From the ion TOF spectra, we obtain the plasma expansion velocity, which depends principally on the effective initial electron temperature. We have obtained values for $T_{e,0}$ as a function of the original Rydberg atom density and binding energy. Our results show that the electron temperature is determined principally by the plasma environment when the UNP decouples from the Rydberg atoms, which occurs when the plasma electrons become too cold to ionize the remaining Rydberg population. Furthermore, the dependence of the electron temperature on Rydberg atom density gives strong indirect evidence for the existence of a bottleneck in the spectrum of Rydberg states that coexist with a cold plasma [3].

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Design of a highly stable Single Ion Microscope

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In recent years, continuous extraction of chromium ions [1] and lithium ions [2] from a magneto optical trap with subsequent focussing has been demonstrated. The aim is to produce beams of cold ions with high brightness and low velocity, as well as to achieve a high resolution. Our approach is individual laser-cooled ions, which can be extracted deterministically from a linear Paul trap and which allow for a novel method of microscopy with a spatial resolution of a few nanometers [3]. The actual experimental setup is using a deterministic single ion source as transmission microscope to reach a focus of 6 nm, limited by mechanical vibrations and thermal drifts. The significant increase of the signal-to-noise ratio compared with conventional Poissonian sources is advantageous.
Two main goals would largely widen the range of applications and facilitate the operation of the Ca-single ion microscope: we aim for a focus spot of 1 nm or below and we envision a single ion rate in the range of kHz for fast data aquisition. Both points are addressed by a compact, highly stable trap and interchangeable and stackable modules. Mechanical stability will be realized by taking advantage of a Ca^+ reservoir, from where single iones are shuttled [4] to the ion segment from where ions are extracted from the the trap and steered into the focussing einzellens. The ions with loading and extraction rates of several kHz are focused at short distances of few 100 nm above the surface with an interaction length of 100 μm in order to be analyzed. The particles are recorded in a detector after the interaction. With a frame piezo, samples can be brought close to the spot of the cold beam. It can be adjusted by (100x100x10) μm and the fine positioning is in the sub-nm range. The surface investigation includes quickly interchangeable samples through a lock.
Furthermore, it is planned to capture the ion again after the interaction in a second Paul trap at a distance of 20 cm from the first one and to detect its quantum state. This will allow for energy loss spectroscopy with ions that are directed near surfaces to be investigated, the ion is used as a probe for electrical and magnetic fields or for the examination of nanoprocessed and microstructured samples.

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P5

Resolving carrier dynamics at sub-nanosecond temporal and sub-micron spatial scales in a SEM

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The aim of ultrafast electron microscopy (UEM) is to resolve (structural) dynamics in space and time at (sub) picosecond temporal scale and (sub) nanometric spatial resolutions. Electron pulses are typically generated by triggering the electron source with an ultrafast laser pulse. The sample is also excited with a laser pulse and subsequently probed with the electron pulse, by varying the time delay of the probe with respect to the pump pulse the dynamics in time is resolved. [1,2]

The combination of a pulsed electron beam and pulsed laser opens up the capability to resolve carrier dynamics on surfaces in space and time in an ultrafast SEM, as shown by the groups of Zewail and Mohammed. [3,4] Visualization of free carrier dynamics is relevant because it critically influences performance and efficiency of photovoltaic devices, photodetectors and other solid state nanodevices.

So far, in these studies, the optical pump is focused to about 30 μm while the electron probe is focused in a spot of size of the order of 10 nm, resulting in a ~3-4 orders of magnitude difference between the spatial extent of pump versus probe pulse. Here, we aim to decrease this gap focusing the optical pump to a diffraction-limited focus. This makes it impossible to study the generation and motion of carriers at the level of a single nanodevice exciting the nanostructure with a tightly focused spot. In addition, high-k vectors may enable efficient coupling between the nanostructure and the laser pulse, for example to launch surface plasmons.

Our setup, consisting of a Quanta 200 FEG SEM, is equipped with an inverted optical microscope below the sample enabling the use of high NA objective lenses. [5] By pre-compensating the dispersion of the objective lens and vacuum window we are able to create 15 fs laser pulses in a 620 nm FWHM focal spot. The electron beam is pulsed by employing an electrostatic beam blanker, leading to 90 ps pulses.[6]

We show first proof of principle pump-probe measurements on semiconductor nanostructures with the goal of mapping carrier diffusion with nanometeric spatial resolution and sub-nanosecond temporal resolution.

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P6

Neutral atom imaging using a pulsed electromagnetic lens

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This poster describes the design, construction, and characterization of a new type of aberration-corrected, neutral-atom lens. Atom beam control plays a crucial role in many different fields, ranging from fundamental physics research and materials science to applied nanotechnology. Despite this, atom-optical elements like lenses and mirrors remain relatively underdeveloped compared to their counterparts in other optics fields. Though aberration correction is addressed quite comprehensively in photon and electron lenses, no credible research efforts have yet produced the same technology for neutral atoms.

We report on progress towards a neutral atom imaging device that will be useful in a range of applications, including nanofabrication and surface microscopy. Our novel technique for improving refractive power and correcting chromatic aberration in atom lenses is based on a fundamental paradigm shift from continuous, two-dimensional focusing to a pulsed, three-dimensional approach. Simulations of this system suggest that it will pave the way towards the long-sought goal of true atom imaging on the nanoscale [1]. We construct a prototype lens and show that all of the technological requirements for the proposed system are easily satisfied. Using metastable neon from a supersonic source, we characterize this prototype for three different focal lengths and a diverse range of apertures [2]. Despite some manufacturing imperfections, we observe lower distortion and higher resolution than has been shown in any previous hexapole lens. Comparison with simulations corroborates the underlying theory and encourages further refinement of the process.

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Crystalline orientation effect on ion backscattering and secondary electron emission from Si crystal surfaces

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The scanning ion microscope (SIM) has attracted recent interest because it allows minute observation of nanostructures. The SIM constructs an image of a sample surface by scanning an ion beam across the surface and detecting secondary electrons (SEs) and backscattered ions (BSIs). SIM images provide a channeling contrast that is derived from the variation in crystallographic orientation of crystalline samples relative to the beam. The crystalline orientation effect on the BSI and SE yields of Si crystal surfaces was investigated at tens-of-keV energies relevant to SIMs by a molecular dynamics simulation [1] to model ion channeling, where the semi-empirical model was added for SE emission [2]. Most interest of this study was placed on the sample damage effect on the channeling contrast in the SIM.

Since the damage depth reaches 100 nm and more for the irradiation with tens-of-keV ions relevant to the SIM, a long rectangular cell of Si with small base along [001] was taken as the simulation cell, $a \times a \times 200a$, where a is the lattice constant. The BSI and SE yields were calculated as mean values for the irradiation with 10^3 ions that were incident on random positions on the small base at an angle, ϕ, measured from the direction of [011]; the angle was changed toward [101]. By no considering any crystalline effects such change in ϕ yields no change in both the BSI and SE yields. In order to study of the irradiation damage effect on the yields, three different irradiation procedures were used for simulation [3]. The first procedure is that the positions of atoms in a simulation cell were reset to initial positions every time step; no crystalline damage is created during ion penetration in the cell. The second procedure is that the atomic positions were reset to initial positions before next irradiation; low-dose irradiation of 3×10^{14} cm^{-2} is simulated. The third procedure is that the atomic positions were dynamically changed by successive irradiation: high-dose irradiation of 3×10^{17} cm^{-2} is simulated.

By the static irradiation with 30-keV He ions [Fig. 1(a)], some dips were clearly observed in the angle dependence of the BSI yield in addition to a large dip around the angle of 0°, corresponding to the channeling dip along the [011] direction. The dips were deep in the BSI yield but shallow in the SE yield, resulted from long (several 10 to 100 nm) and short (<10 nm) escape depths of BSIs and SEs, respectively. The cumulative irradiation [Fig. 1(c)] caused the angle dependence of the BSI yield to lose their detailed structure, where large scattering in both the BSI and SE yields were produced by recoiling motions of Si atoms by successive irradiation. However, the dips in the BSI yield remained for noncumulative irradiation [Fig. 1(b)], corresponding to an ion dose of 3×10^{14} cm^{-2}, where the dips in the SE yield were unclear. This is because the deep bulk was damaged slowly by the slowed and widely-distributed ion. Another effect of the crystal damage was general reduction of BSI yields arising from an increasing energy transfer from the ions to recoiling atoms, resulting in the damage process of the crystal bulk to be amorphous.

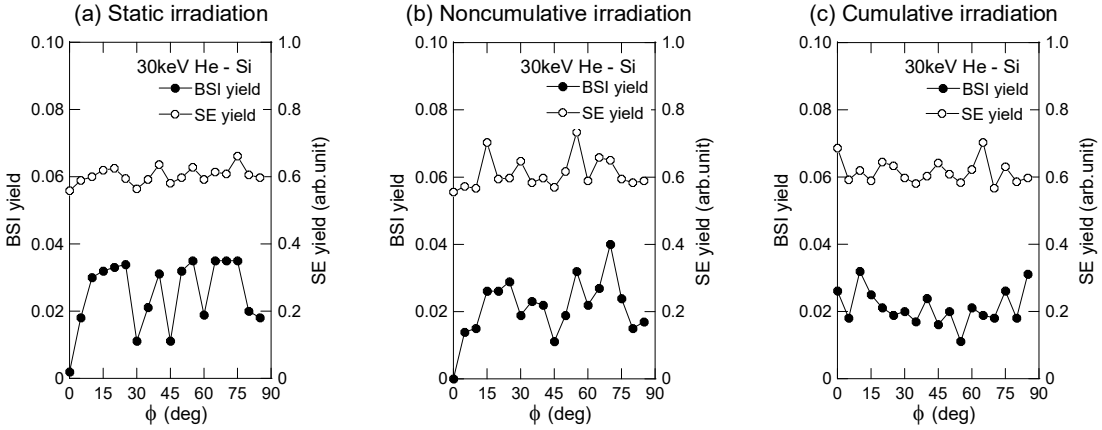

Fig. 1 Angle (ϕ) dependence of BSI and SE yields of a Si crystal irradiated with 30-keV He ions. The noncumulative and cumulative irradiation correspond to low-dose (3×10^{14} cm^{-2}) and high-dose (3×10^{17} cm^{-2}), respectively.

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P8

Deterministic Single Ion Implantation for the formation of nitrogen vacancy centers

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We use a linear Paul trap as a deterministic single ion source and employ it to implant nitrogen vacancy centers (NV centers) into diamond.

Isotopically pure nitrogen-15 gas (98 atom %) is injected into an ion gun. $^{15}N_2^+$ ions are generated by electron impact ionization, accelerated to 500 eV and selected by a Wien filter. The beam is then injected into a linear Paul trap.
The successful trapping of a N_2^+ ion is detected by the position shift of the fluorescence image of a trapped $^{40}Ca^+$ ion, when a two-ion crystal is formed. The calcium ion is cooled by laser radiation, and this process cools sympathetically all motional degrees of freedom of the two-ion crystal.
The ions are extracted from the trap with a voltage of 5.9 keV. During the flight the calcium is separated from the nitrogen ion, which subsequently is focused on the sample with an electrostatic einzellens [1].
For calcium ions we achieve a beam radius of 7 nm, whereas for nitrogen we reach a beam radius of 80 nm due to sympathetic cooling.

To prove that the NV centers originate from our deterministic implantation, we used pulsed optically detected magnetic resonance (ODMR) spectroscopy. With this method we were able to measure the hyperfine splitting of the ^{15}NV center (nuclear spin I = 1/2) and thus verify the implantation.
For this shallow implantation (depth ~5 nm) we obtain a creation yield of the NV centers of 0.6 %.

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P9

Novel Electron Mirror Pulse Compressor for UED and DTEM

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Many atomic processes occur on timescales that are as short as tens to hundreds of femtoseconds. While pulsed lasers have the temporal resolution to investigate these processes, they cannot provide the requisite spatial resolution. Pulsed electron techniques have recently been developed [1] to address such problems. In Ultrafast electron diffraction (UED) and Dynamic transmission electron microscopy (DTEM) an unprecedented combination of spatial and temporal resolution is obtained by illuminating a photocathode with an ultrafast pulsed laser, accelerating the photoemitted electrons and illuminating a specimen with the ultrafast pulse to obtain time-resolved electron diffraction patterns or images. Unfortunately, Coulomb interactions among the electrons broadens the temporal and spatial extent of the pulse during the travel of the beam to the specimen. The Coulomb interactions mainly increase the beam energy spread (Boersch effect) from a fraction of an electron-Volt to hundreds or even thousands of electron-Volts. The Boersch effect has a two-fold impact on the electron optics: it spreads the arrival time window of the pulse from tens of femtoseconds to picoseconds and beyond; and it increases the objective lens chromatic aberration, which reduces the spatial resolution. Consequently, there remains a strong demand for improving the temporal resolution of the probing pulse into the femtosecond range without sacrificing total pulse charge and spatial resolution.

The distribution of the photo-emitted electron velocities becomes linearly chirped [2] - given sufficient propagation - resulting in a linear dependence between the pulse transit time and the energy spread. We have designed a novel electron pulse compressor that can compress a linearly chirped electron pulse at the specimen into the sub-100 femtosecond range and simultaneously correct the chromatic and spherical aberration of the objective lens for improved spatial resolution. The pulse compressor utilizes an electrostatic electron mirror combined with a beam separator composed of a magnetic prism array that allows normal beam entrance to minimize mirror aberrations. After reflection in the mirror, the velocity distribution of the pulse is inverted, as the trailing edge of the pulse has a higher energy than the leading edge. The inversion of the velocity distribution results in the temporal compression of the propagating pulse once the pulse is allowed to drift to the specimen. The mirror can be tuned to accommodate pulses with a varying number of electrons and can be adapted to UED and DTEM columns of different lengths. The combination of the beam separator with the electron mirror allows the axis from the gun to the specimen to remain straight, which simplifies alignment and minimizes aberrations. Furthermore, the static nature of the electron mirror simplifies set-up and tuning of the pulse compressor and thus avoids the jitter problem associated with RF pulse compression techniques [3].

The linear chirp arises from the average electron space charge. In addition, there is temporal blur about the linear profile, which is produced by the stochastic nature of the Coulomb interactions. This blur limits the attainable temporal resolution as it cannot be corrected by the pulse compressor. The FWHM of this distribution ranges from 100 to 200 femtoseconds.

The prism-mirror combination can be simultaneously exploited for the correction of the objective lens aberrations. The electric field in the electron mirror is tuned to not only invert the velocity distribution of the pulse, but also produce aberration coefficients that can compensate the objective lens aberrations. These corrections will become increasingly beneficial as the illuminated area is reduced for carrying out ultrafast diffraction experiments from small regions of the sample, e.g. from individual grains or nanoparticles.

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Microwave cavity resonance spectroscopy on an ultracold plasma

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Recently, we have set up a compact magneto-optical trap, based on a diffractive grating chip [1], for ultracold experiments with Rydberg plasmas. This setup will be used to create a Rydberg plasma, by trapping and laser cooling the atoms of rubidium gas down to $\sim$100 μK and photo-ionizing the atoms near-threshold in a two-step photo-ionization process, using a 780 nm excitation laser and a 480 nm ionization laser.
The rubidium plasma generated is then used in order to study the fundamental interaction between the plasma and the electromagnetic fields inside a resonant microwave cavity. This is done in the context of developing microwave cavity resonance spectroscopy as a novel beam metrology tool in ASML's extreme ultraviolet (EUV) lithography devices. In order to test the fundamental limits of the interaction of a plasma with the electromagnetic fields in a microwave cavity, a well-defined ultracold rubidium plasma, with its distribution shaped by a spatial light modulator, will be used as a model plasma to test the EUV beam monitor with a high accuracy. Moreover, it opens up the possibility to investigate interesting fundamental heating mechanisms in these exotic plasmas, like three-body recombination (which is expected to deviate from conventional ultracold plasma physics in the presence of a microwave electric field [2]).

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A reaction microscope for few-body Rydberg dynamics

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On the basis of our deterministic ion source experiment, we are developing a reaction microscope that is inspired by the well-known MOTRIMS technique. For this, a sample of 10^6 ^{87}Rb atoms will be prepared in a crossed dipole trap. Using a 3-level excitation scheme, some atoms can be excited to atomic or molecular Rydberg states. After a short evolution time, these Rydberg excitations are photoionised by a short laser pulse from a high power CO_2 laser. The produced ions follow small homogeneous electric fields generated by Wiley-McLaren-type ion optics and are subsequently detected by a time and position sensitive micro channel plate detector. By analysing the trajectories of the recoil ions, we aim to measure momentum distributions of Rydberg molecule wave functions. In this context, special focus lies on butterfly and trilobite molecules, which can be addressed efficiently due to the opportunity of exciting Rydberg p- and f-states. As a next step, stroboscopic monitoring of the internal decay of Rydberg molecules as well as measurements regarding forces between pairs of Rydberg atoms will be performed.

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The AC-MOT Cold Atom Electron/Ion Source

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Extracting an electron or ion beam from a magneto-optical trap (MOT) requires either the beam be perturbed by the trapping magnetic fields of the MOT as it is extracted [1], or if the magnetic fields are switched off and any induced eddy fields allowed to decay before extraction, a significant reduction in trap density and hence possible beam current [2]. To enable magnetic field free extraction whilst retaining a high trap density this experiment uses an alternating current MOT (AC-MOT). In the AC-MOT, the trapping laser polarisation is switched synchronously with an sinusoidal magnetic field, allowing the trapping fields to be switched to zero in less than 100 μs, $\sim$ 60 times faster than for a conventional MOT (DC-MOT) [3]. Once the magnetic fields are zeroed the atoms are ionised in a pulsed, two colour photo-ionisation scheme and the ions or electrons are extracted by electrostatic fields.

A new source has been built in Manchester to explore the benefits of an AC-MOT driven cold atom electron/ion source (CAEIS) by performing a range of electron diffraction experiments.

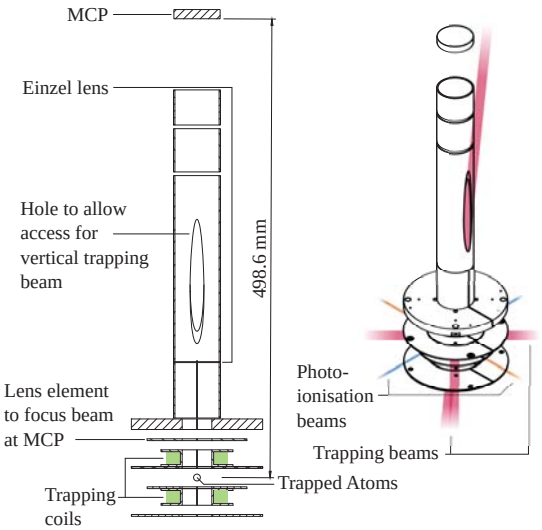

Figure 1: (Main): A cross-section of the cold atom electron/ion source. Electrons are extracted upwards by biasing the MOT coil plates. (Insert): A 3D render showing the trapping (red) and ionisation (blue, orange) laser beams.

The new source is currently being characterised and the brightness of the electron beams produced using an AC-MOT is being compared to those produced using a DC-MOT. Whilst at higher energy, simulations have suggested that there is limited benefit from the AC-MOT, for low energy beams the improvement in brightness could be significant.

Determining the brightness, $\mathscr{B}$, of a charged particle beam requires its current, $\mathbf{J}$, and characteristic temperature, T, to be measured, since

$$\mathscr{B} = \frac{\mathbf{J}}{4\pi}\frac{mc^2}{k_b T}.$$

The charge and temporal profile of the bunches making up the beam are measured using a charge pick off circuit, whilst the bunch temperature is determined from the expansion of the beam over the $\sim$500 mm beam line [1]. Figure 1 shows a schematic of the electrodes that make up the beam-line and produce the extraction and focusing electrostatic fields, as well as showing the location of the trapping coils and the 6 counter-propagating laser beams that make up the MOT. The two photo-ionisation beams are also illustrated. A description of the source, details on the temperature measurements, and a comparison between an AC-MOT and a DC-MOT CAEIS will be presented.

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Energy spread measurements of an ultracold Rb^+ beam

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The resolution of a focused ion beam (FIB) is determined by a combination of the transverse reduced brightness of the ion beam and abberations of the electrostatic lens system. The most important of these abberations, especially at low currents at which the ultimate resolution is obtained, is often chromatic abberation; the phenomenon that ions with a different energy are focused at a different position. Thus reducing the energy spread of the ion beam leads to an improved FIB resolution. In this research the energy spread of an ultracold Rb^+ beam is determined by using a retarding field energy analyzer (RFEA).

This Rb^+ beam is formed by photoionization of a laser-cooled and compressed atomic beam originating from a Knudsen source. The laser-cooled atomic beam is selected with an aperture that can be varried in size in order to set the desired current. A two-step photoionization process takes place at the overlap of a cylindrically focused excitation laser beam (780 nm) and a cavity-enhanced ionization laser beam (480 nm). In order to suppres disorder-induced heating which may lower the ion-beam's brightness, the ionization takes place in an electric field that quickly separates the created ions [1]. In a second stage, the ion beam is accelerated to its final energy in the range 50 eV-8 keV. The resulting energy spread is mostly determined by the distribution of longitudinal positions at which the ions are created, which translates in an energy distribution due to the applied electric field.

The energy spread of the created ion beam is analyzed in a custom-built RFEA. This RFEA is based on the design by Simpson [2], which contains two decelerating sections and two accelerating sections. Having two decelerating sections allows setting the fields such that the beam has a waist on the center plate at which the analysis takes place. The voltage on this plate is varied in order to either transmit or reflect the incoming ions. By means of particle tracing simulations with the "General Particle Tracer" software [3] the settings were found at which the energy resolution of the analyzer was optimal. At the lowest electric field and an energy of 1 keV the apparent energy spread due to the detector was ≈40 meV, but the resolution was found to be dependent on the beam energy and the used acceleration field.

The energy spread is measured for different excitation laser intensities, ionization laser intensities, currents, electric fields and beam energies. The lowest full-width-at-half-maximum (FWHM) energy spread measured is 0.22 eV at a beam energy of 1 keV, a current of 10 pA and an acceleration field of 35 kV/m. As expected the energy spread does not change much as a function of beam energy. For larger currents the distribution becomes slightly wider; 0.37 eV for 280 pA. The energy distributions at different laser intensities agree well with calculations of the ionization position distribution based on numerical solutions to the optical Bloch equations. The energy spread is significantly lower than the energy spread of a gallium liquid metal ion source (5 eV FWHM [4]) and comparable to that of a helium field emission source (0.29 eV FWHM [5]).

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Optically Imprinted Rydberg Atom Lattice

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Storing laser-cooled Rydberg atoms in a lattice offers the possibility to simulate a broad range of quantum processes. Van der Waals forces for Rydberg atoms are many orders of magnitude greater than those of ground state atoms, allowing strong correlations to be induced as required for a quantum simulator. By shaping light with a spatial light modulator [1] and employing interaction-induced blockade phenomena, such a lattice can be created from a random gas as provided by a magneto-optical trap. Previously, we have demonstrated spatial imaging of Rydberg atoms with few-micron resolution leading to the observation of a blockade radius in the pair correlation function. Improved control over Rydberg excitation has been implemented by referencing the laser frequency to a narrow, ultra-stable cavity and using 2-photon excitation to access Rydberg physics. We are currently working on understanding the 2-photon excitation from both 2-level and 3-level perspectives to investigate Rydberg interactions. Eventually, we want to create one Rydberg atom per lattice site and create controlled interactions as required for quantum simulation.

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Ultrafast LEED: Exploring surface dynamics with short electron pulses

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Low-energy electron diffraction (LEED) is one of the prime techniques of surface science, allowing for detailed insights into a variety of phenomena such as structural phase transitions, surface reconstructions or chemical reactions [1]. Yet, many of these features exhibit highly-complex couplings and correlations between the electronic, magnetic and structural degrees of freedom, which are difficult to disentangle using steady state analyses of systems in equilibrium. While the electronic and spin systems are already extensively studied at surfaces on their intrinsic timescales, gaining experimental access to ultrafast structural evolution remains challenging. Hence, in order to reach a comprehensive and quantitative understanding of ultrafast dynamics at surfaces, a time-resolved implementation of LEED is highly desirable.

Here, we present the development of ultrafast low-energy electron diffraction (ULEED), employing low-energy electron pulses in a laser-pump/electron-probe scheme. Within this approach, a laser-triggered nanoscopic needle emitter is utilized in a miniaturized electrostatic lens geometry as a high-brightness source. The resulting electron pulses exhibit a minimal duration down to 1 ps at the sample for electron energies of 20-200 eV.

We demonstrate the potential of ULEED by investigating the optically induced transition between charge density wave (CDW) phases at a single-crystalline 1T-TaS_2 surface [2,3]. We also apply ULEED to study the dynamics of adsorbates on metal surfaces.

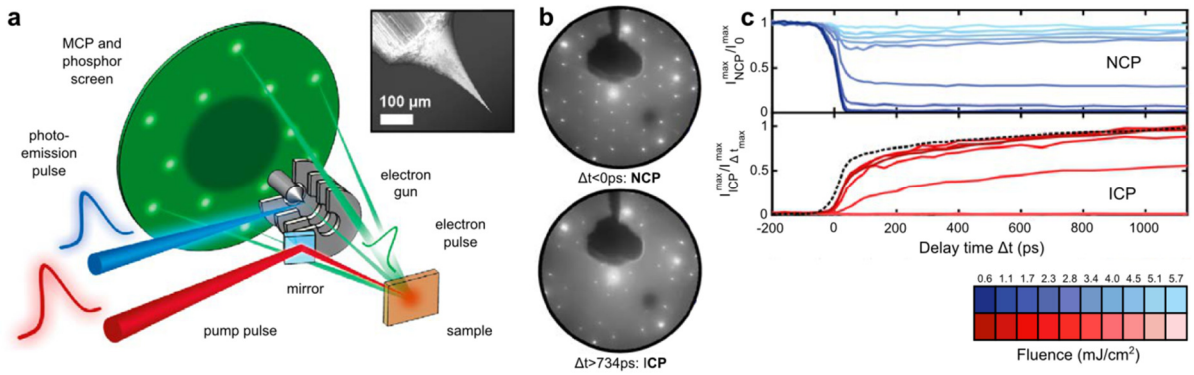

Figure 1: Ultrafast LEED: **a)** Experimental setup; **b)** Diffraction images of 1T-TaS_2 taken before and shortly after optical excitation reveal the ultrafast transition between CDW phases; **c)** Temporal evolution of CDW spot intensities.

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Experimental Realisation of Quantum Rabi Model in Ultracold Atoms

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The Quantum Rabi model describes the interaction between a two-level quantum system and a single bosonic mode. The strong-coupling regime and ultra-strong coupling regime have been studied experimentally but the deep strong coupling regime is inaccessible to experiments using natural light-matter interactions. So, we explore ultracold rubidium atoms in a periodic optical lattice superimposed with a harmonic trapping potential, with the two-level system represented by the occupation of Bloch bands of the lattice. The motion of the atoms trapped in the optical dipole potential acts as a quantum harmonic oscillator, that couples with the optical lattice. This provides access to the previously unattainable extreme parameter regimes, including the crossover between ultra-strong and deep strong coupling. In this regime, a pattern of collapse and revival is predicted to be observed.

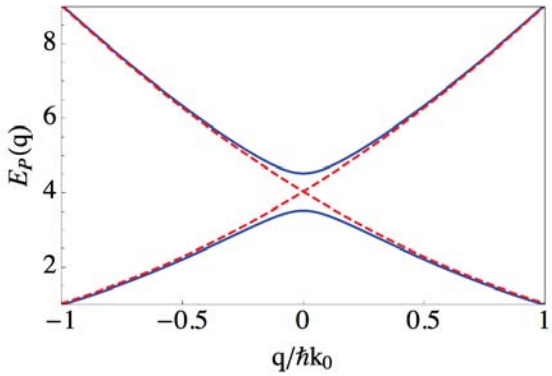

Figure 1: Band Structure for an optical lattice potential.[1]

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Pulse length measurements of ultracold and ultrafast electron bunches extracted from a laser cooled gas

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We are developing an ultrafast and ultracold electron source, based on near-threshold, femtosecond photoionization of laser-cooled and trapped Rubidium gas. Recently, we demonstrated electron crystallography of graphite for the first time using the ultracold source. The ultimate goal is ultrafast, single-shot electron crystallography of macromolecules, which requires a high degree of control of the dense electron phase space distribution. The transverse phase space distribution was characterized using the waistscan method and yielded electron temperatures as low as 10 K. For characterizing the longitudinal phase space distribution we have developed a microwave cavity based diagnostic element to correlate electron bunch lengths to streak images. This allows us to measure the pulse length with sub picosecond temporal resolution[1]. We present the first measurements of *both* ultracold *and* ultrafast electron pulses which have an rms pulse duration of 20 picoseconds containing at least 1000 electrons. These bunches are sufficiently short to be compressed to 100 fs bunch lengths using established RF compression techniques.

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