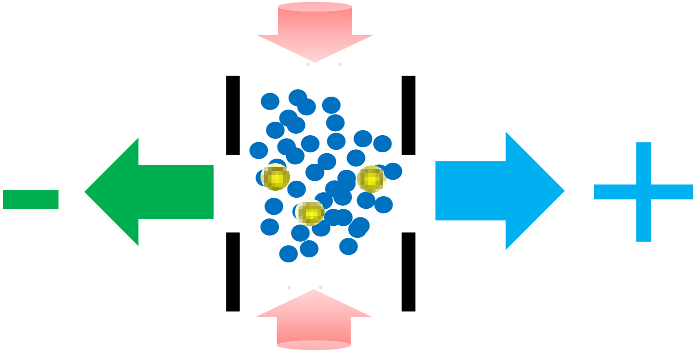
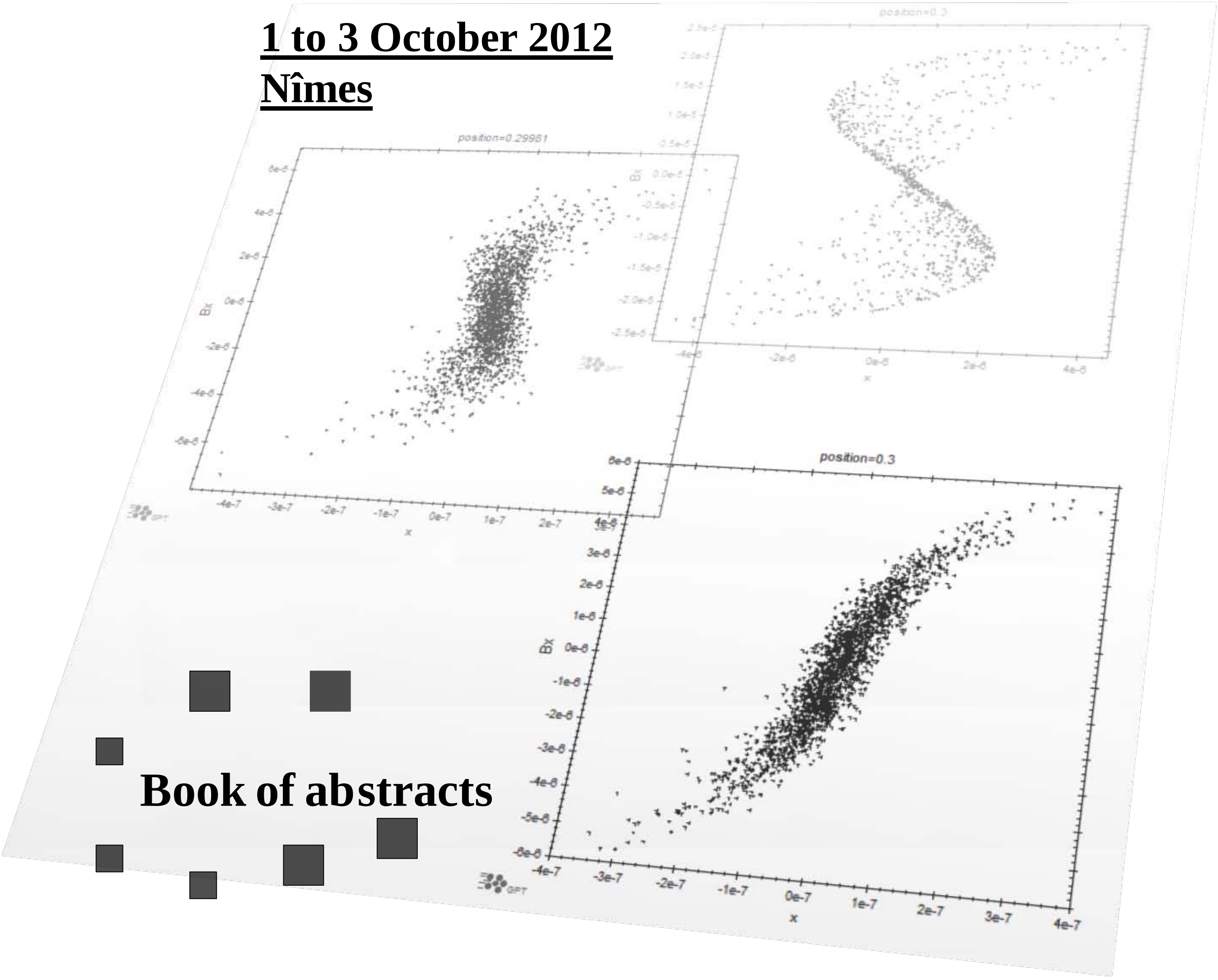
Coldbeams : ultra-COLD gas for Bright Electron and Monochromatic ion Source

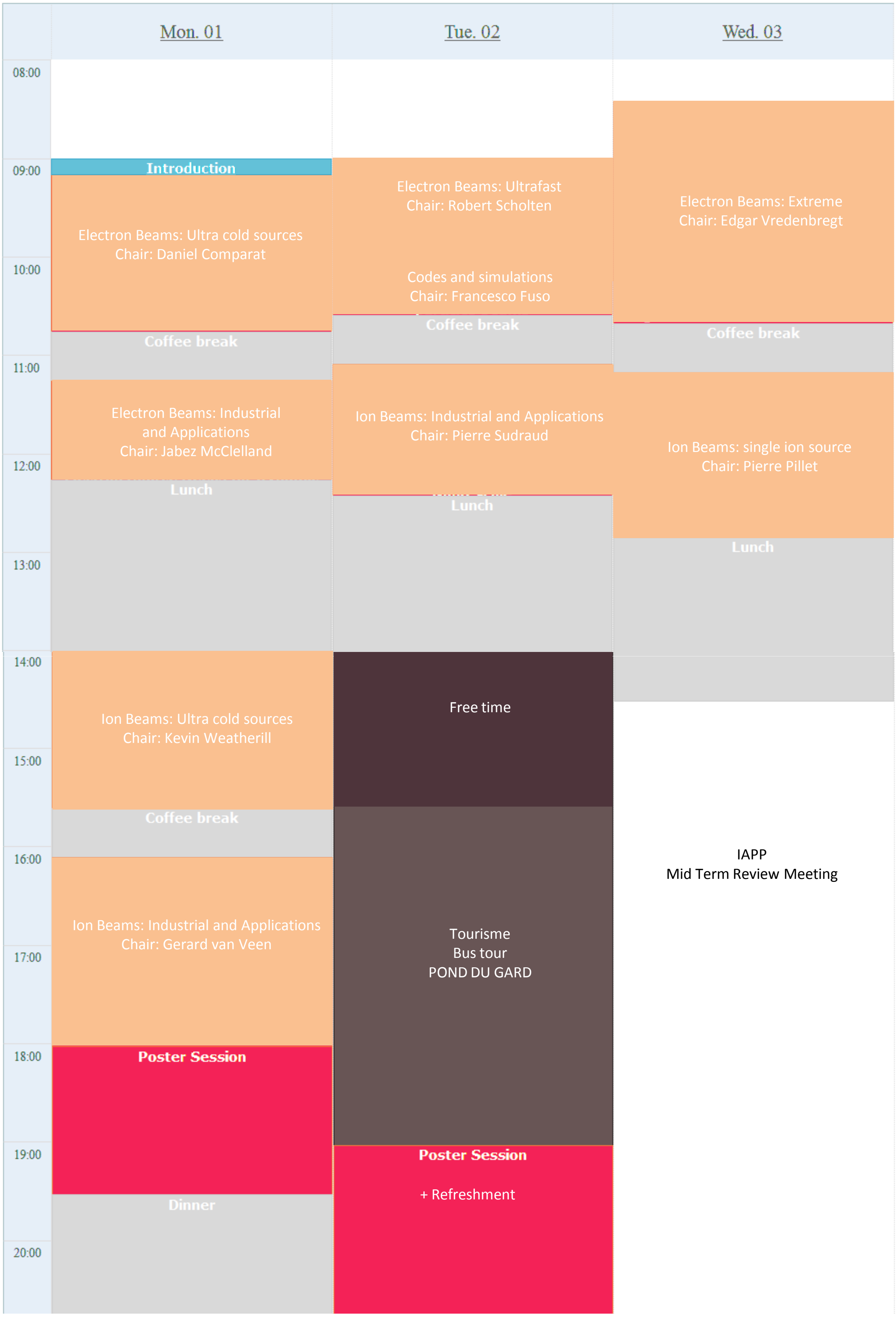




1 to 3 October 2012
Nîmes

Book of abstracts

http://coldbeams.sciencesconf.org



	Mon. 01	Tue. 02	Wed. 03
08:00			Electron Beams: Extreme Chair: Edgar Vredenbregt
09:00	**Introduction** Electron Beams: Ultra cold sources Chair: Daniel Comparat	Electron Beams: Ultrafast Chair: Robert Scholten	
10:00	**Coffee break**	Codes and simulations Chair: Francesco Fuso **Coffee break**	**Coffee break**
11:00	Electron Beams: Industrial and Applications Chair: Jabez McClelland	Ion Beams: Industrial and Applications Chair: Pierre Sudraud	Ion Beams: single ion source Chair: Pierre Pillet
12:00	**Lunch**	**Lunch**	**Lunch**
13:00			
14:00	Ion Beams: Ultra cold sources Chair: Kevin Weatherill	Free time	IAPP Mid Term Review Meeting
15:00	**Coffee break**	Tourisme Bus tour POND DU GARD	
16:00	Ion Beams: Industrial and Applications Chair: Gerard van Veen		
17:00			
18:00	**Poster Session**		
19:00	**Dinner**	**Poster Session** + Refreshment	
20:00			

COLDBEAMS Workshop

http://coldbeams.sciencesconf.org/

The primary purpose of the COLDBEAMS workshop is to discuss the state-of-the-art of ion/electron sources based on ultra-cold atoms and their potential applications in different fields, microscopy nanofabrication, imaging or spectroscopy. The intention of the workshop is to bring together scientists working on the sources – many of whom are in the cold atom community – with those working with “conventional” electron and ion sources on a range of interesting applications. It also includes members of the community of commercial suppliers of ion and electron beam systems to gain from their perspective on this new technology. Both the fundamental and technological aspects of the processes behind the production of these very mono-chromatic, extreme spatial or temporal controlled charged beams will be covered. We aim to pool common areas of interest, advancing current technological limits by fostering and encouraging collaboration. There will be ample opportunity to discuss issues from the experimental, theoretical and applicative activities with the goal to enhance knowledge sharing and inter-sector mobility activities.

Scientific committee

Daniel Comparat, Pierre Pillet	Laboratoire Aimé Cotton, Orsay
Franscesco Fuso	University of Pisa
Jabez McClelland	NIST Gaithersburg
Pierre Sudraud	Orsay Physics, SME
Robert Scholten	University of Melbourne
Gerard van Veen	FEI Company
Edgar Vredenbregt	Technische Universiteit Eindhoven
Kevin Weatherill	Durham University, UK

Organisation committee

Daniel Comparat, Yoann Bruneau	Laboratoire Aimé Cotton, Orsay

Financial support

The workshop has been organized to cover the scientific goals of the following European Union Seventh Framework Programs:

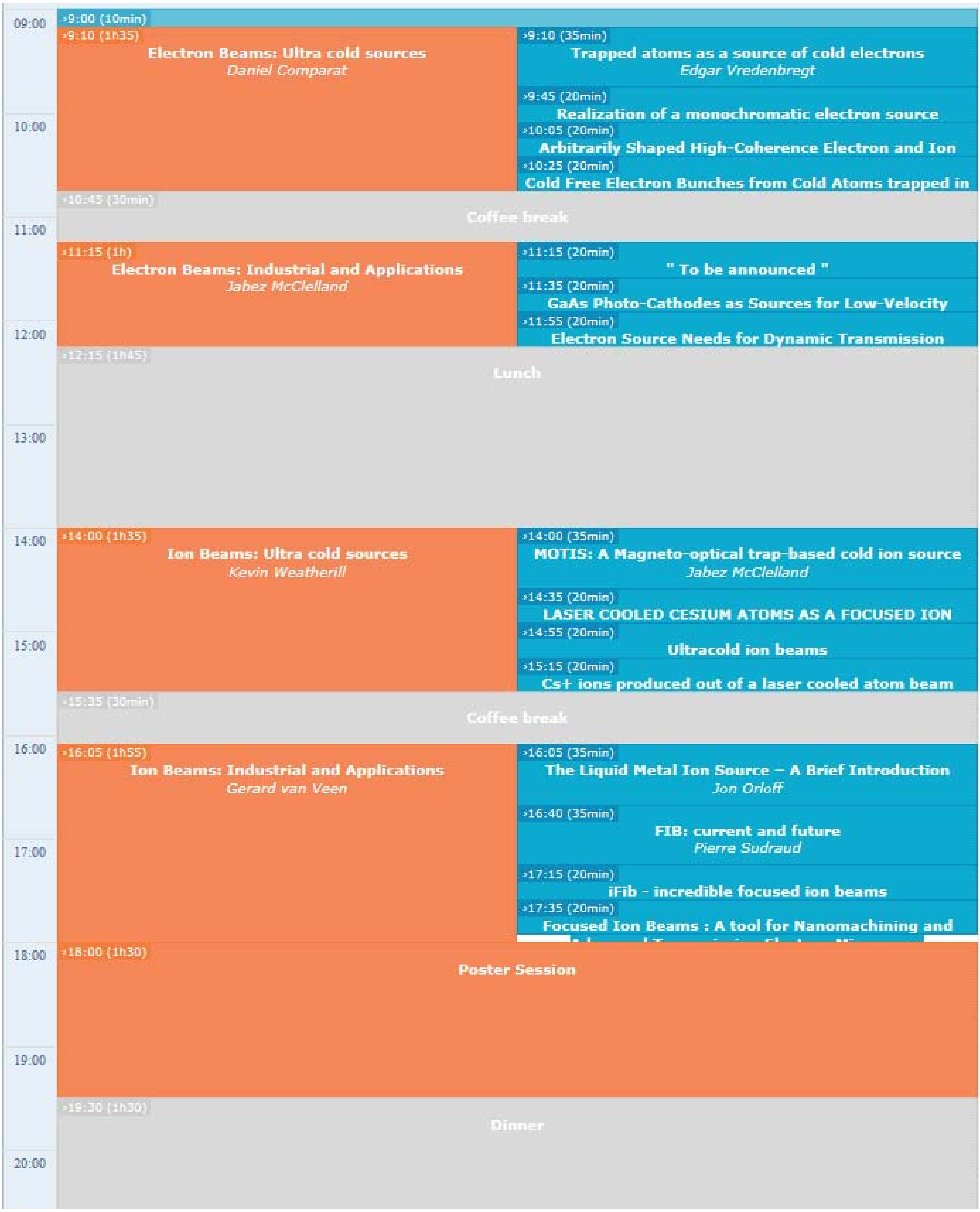
- Marie Curie Industry-Academia Partnerships and Pathways: FP7-PEOPLE-2009-IAPP COLDBEAMS (ultra-COLD gas for the production of a Bright Electron And Monochromatic ion Source) under grant agreement n. 25139.
- European Research Council Starting Grants 2011 under the ERC COLDNANO (UltraCOLD ion and electron beams for NANOscience) grant agreement n. 277762.

Therefore every participant has been chosen to have direct linked to these projects. The expenses needed to organize the meeting: scientific meeting followed by the IAPP Mid Term Review meeting, are thus mainly paid under these grants. Sponsors complete the support:

Orsay Physics

ARC Centre of Excellence in Coherent X-ray Science (CXS)

Planning Monday, October 1, 2012



09:00

›9:00 (10min)

›9:10 (1h35)
Electron Beams: Ultra cold sources
Daniel Comparat

›9:10 (35min)
Trapped atoms as a source of cold electrons
Edgar Vredenbregt

›9:45 (20min)
Realization of a monochromatic electron source

10:00

›10:05 (20min)
Arbitrarily Shaped High-Coherence Electron and Ion

›10:25 (20min)
Cold Free Electron Bunches from Cold Atoms trapped in

›10:45 (30min)
Coffee break

11:00

›11:15 (1h)
Electron Beams: Industrial and Applications
Jabez McClelland

›11:15 (20min)
" To be announced "

›11:35 (20min)
GaAs Photo-Cathodes as Sources for Low-Velocity

›11:55 (20min)
Electron Source Needs for Dynamic Transmission

12:00

›12:15 (1h45)
Lunch

13:00

14:00

›14:00 (1h35)
Ion Beams: Ultra cold sources
Kevin Weatherill

›14:00 (35min)
MOTIS: A Magneto-optical trap-based cold ion source
Jabez McClelland

›14:35 (20min)
LASER COOLED CESIUM ATOMS AS A FOCUSED ION

›14:55 (20min)
Ultracold ion beams

15:00

›15:15 (20min)
Cs+ ions produced out of a laser cooled atom beam

›15:35 (30min)
Coffee break

16:00

›16:05 (1h55)
Ion Beams: Industrial and Applications
Gerard van Veen

›16:05 (35min)
The Liquid Metal Ion Source – A Brief Introduction
Jon Orloff

›16:40 (35min)
FIB: current and future
Pierre Sudraud

17:00

›17:15 (20min)
iFib - incredible focused ion beams

›17:35 (20min)
Focused Ion Beams : A tool for Nanomachining and

18:00

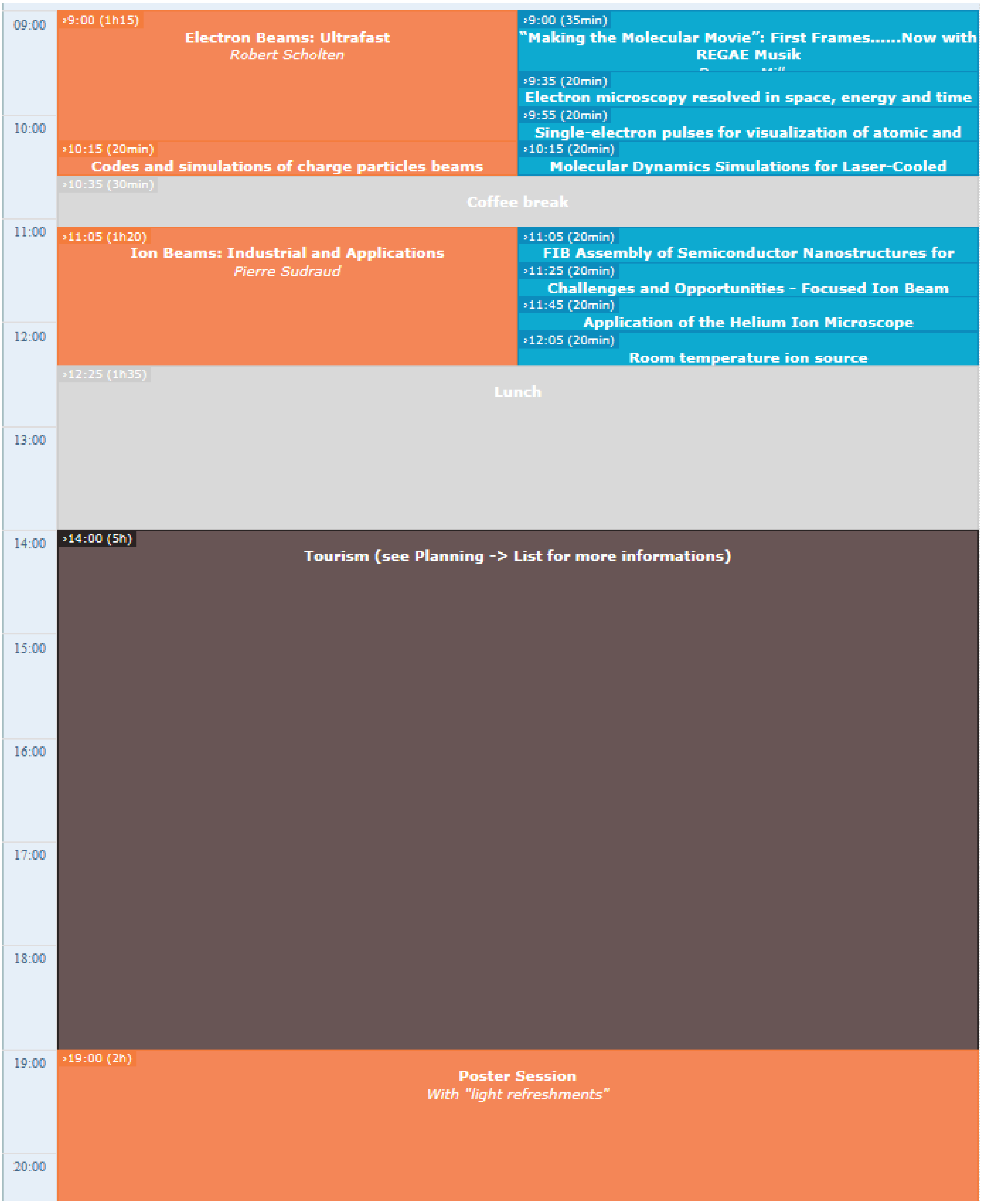
›18:00 (1h30)
Poster Session

19:00

›19:30 (1h30)
Dinner

20:00

Planning Tuesday, October 2, 2012



09:00

›9:00 (1h15)

Electron Beams: Ultrafast

Robert Scholten

›9:00 (35min)

"Making the Molecular Movie": First Frames......Now with REGAE Musik

›9:35 (20min)

Electron microscopy resolved in space, energy and time

10:00

›9:55 (20min)

Single-electron pulses for visualization of atomic and

›10:15 (20min)

Codes and simulations of charge particles beams

›10:15 (20min)

Molecular Dynamics Simulations for Laser-Cooled

›10:35 (30min)

Coffee break

11:00

›11:05 (1h20)

Ion Beams: Industrial and Applications

Pierre Sudraud

›11:05 (20min)

FIB Assembly of Semiconductor Nanostructures for

›11:25 (20min)

Challenges and Opportunities - Focused Ion Beam

›11:45 (20min)

Application of the Helium Ion Microscope

12:00

›12:05 (20min)

Room temperature ion source

›12:25 (1h35)

Lunch

13:00

14:00

›14:00 (5h)

Tourism (see Planning -> List for more informations)

15:00

16:00

17:00

18:00

19:00

›19:00 (2h)

Poster Session

With "light refreshments"

20:00

Planning Wednesday, October 3, 2012

08:00
09:00
10:00
11:00
12:00
13:00
14:00

›8:25 (2h15)
Electron Beams: Extreme
Edgar Vredenbregt

›8:25 (35min)
Electron and X ray Beam with Laser-plasma accelerators
Victor Malka

›9:00 (20min)
Time-of-Flight Aberration Correction and Spin Filtering

›9:20 (20min)
CsBr based photoelectron nano sources

›9:40 (20min)
Low-energy (0-20 eV) Electron Beam for Chemical

›10:00 (20min)
Ultrafast Molecular Imaging With Laser-Driven Electron

›10:20 (20min)
Ring-cathode focused electron beam columns

›10:40 (30min)
Coffee break

›11:10 (1h40)
Ion Beams: single ion source
Pierre Pillet

›11:10 (20min)
Ion emission from a dipole blocked cold atomic gas.

›11:30 (20min)
NOVEL ION TRAPS FOR DETERMINISTIC ION

›11:50 (20min)
Bypassing Liouville: Deterministic single-ion-implanted

›12:10 (20min)
A laser-cooled Si atom source for Kane quantum

›12:30 (20min)
Single ion implantation for nanoelectronics and the

›12:50 (1h40)
Lunch

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Electron Beams: Industrial and Applications

Monday, October 1, 2012 - 14:00 - 15:35

Ion Beams: Ultra cold sources

Monday, October 1, 2012 - 16:05 - 18:00

Ion Beams: Industrial and Applications

Monday, October 1, 2012 - 18:00 - 19:30

Poster Session

Trapped atoms as a source of cold electrons

Edgar Vredenbregt, Eindhoven University of Technology

Electron microscopy and diffraction have long been used to study the structure of materials. A recent development is the achievement of ultrafast time resolution using high-repetition rate single electron sources and single-shot many-electron sources. Achieving large coherence lengths under these conditions is challenging due to intrinsic heating mechanisms including inter-particle Coulombic forces. Near-threshold, pulsed photoionization of atoms trapped and cooled with lasers is being investigated as a means to produce intense electron pulses with large intrinsic coherence length due to a low electron temperature. Photo-ionizaton sources are, of course, not an entirely new idea but recent implementations using trapped atoms offer new possibilities. Several properties of electron beams extracted from such ultracold sources have already been investigated, showing in particular that temperatures of a few Kelvin and emittances in the nanometer-radian range can be achieved with tens of thousands electrons per pulse for nanosecond pulse lengths. This can be combined with delicate shaping of the charge distribution to counteract emittance growth due to non-linear self fields. Using ultrafast lasers for the ionization step, shorter electron pulses can be achieved, but an interesting question is whether the concomitant spread in photon energy still allows for low electron temperature. Recent experiments have shown that few-Kelvin temperatures combined with picosecond pulse lengths are indeed possible. It turns out that this can be understood with a classical model for electron trajectories resulting from photoionization. In addition, experimentally observed polarization effects are in general agreement with model results.

Realization of a monochromatic electron source

Yoann Bruneau, Laboratoire Aimé Cotton, Université Paris Sud 11, Bât. 505, 91405 Orsay, France

In order tostudy surfaces or to make reaction on a surface at a precise position, we need to create electrons beams of few eVs with high brightness: focused on a tiny spot and with a low energy. The purpose is to connect our experiment with AnneLafosse's experiment at Orsay (see her talk) in which the team usesintense electron beam but on a spot of several mm. With our experiment, we should have an electron beam 1000 times better in terms of current dentity and of focusing size. This talk will present how a 2D-Magneto Optical Trap (MOT) can create such a beam.

Our experiment is based on a 2D-MOT. We cool Cs atoms in 2 dimensions. On the last dimension we apply a pushing beam to accelerate the atoms in a specific direction and create a continuous atomic beam with a high flux near 10^{10} atoms per second. With this flux, it is possible to create ~1 nA electron beams. A study on the power, the shape and the wavelength of the pushing beam has been achieved to control the flux of atoms in the ionization area. Permanents magnets can also be added to create a magnetic field gradient and compress the atomic beam and control the flux of atoms in the ionization area.

We shall then study the ionization of the atoms and how to focalize them on small surface while restricting the energy scattering. Simulations with General Particle Tracer (GPT) software have been performed, while changing the current of the electron beam, the initial position of the electrons and the paraxial aberrations, to know what minimum surface can be achieved with our apparatus.

Arbitrarily Shaped High-Coherence Electron and Ion Bunches from Laser-Cooled Atoms

R. E. Scholten, A. J. McCulloch, D. J. Thompson, D. Murphy, C. T. Putkunz and
D. V. Sheludko
*ARC Centre of Excellence for Coherent X-ray Science, School of Physics,
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scholten@unimelb.edu.au

Ultrafast electron diffractive imaging of biological molecules and defects in solid state devices can provide valuable information on dynamic processes at the nanoscale. The effective brightness of electron sources has been limited by non-linear divergence caused by repulsive interactions between the electrons, known as the Coulomb explosion. It has been shown that electron bunches with ellipsoidal shape and uniform density distribution have linear internal Coulomb fields,[1] which allows for reversal of Coulomb explosion using conventional optics. Charged particle sources based on photoionisation of laser cooled atoms can in principle create bunches shaped in three dimensions and hence achieve the transverse spatial coherence and brightness needed for picosecond diffractive imaging with nanometre resolution.

We have recently demonstrated[2] such arbitrary shaping of the cold atom cloud (Fig. 1), and hence of the extracted electron bunches (Fig. 2a), and used the shaping capability to allow detailed measurement of the spatial coherence properties of the cold electron source.[3] We also show remarkable ion bunch shape formation and evolution, with direct visualisation made possible by the very low (milli-Kelvin) temperature of the ions (see Fig. 2b). We have successfully simulated the ion bunch formation using a four-level optical Bloch equation model incorporating ionisation loss. Using two-step coherent excitation with a femtosecond laser from ground to excited state, and a nanosecond laser from excited state to the continuum, we have produced sub-nanosecond (or less) electron pulses. Diffraction experiments of simple crystalline materials are currently in progress, to demonstrate application of the high coherence of the novel source.

In separate work,[4] we have demonstrated coherent diffractive imaging with electrons in scanning transmission electron microscopy. Future development of the cold atom electron source will increase the bunch charge and charge density, demonstrate reversal of Coulomb explosion and picosecond pulse durations, and ultimately, ultrafast coherent electron diffractive imaging.

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[1] O. J. Luiten, S. B. van der Geer, M. J. de Loos, F. B. Kiewiet, and M. J. van der Wiel, Phys. Rev.Lett. **93**, 094802 (2004); B. J. Claessens, S. B. van der Geer, G. Taban, E. J. D Vredenbregt, and O. J. Luiten, Phys. Rev. Lett. **95**, 164801 (2005).

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[4] C. T. Putkunz *et al.*, Phys Rev Lett, **108** 073901 (2012).

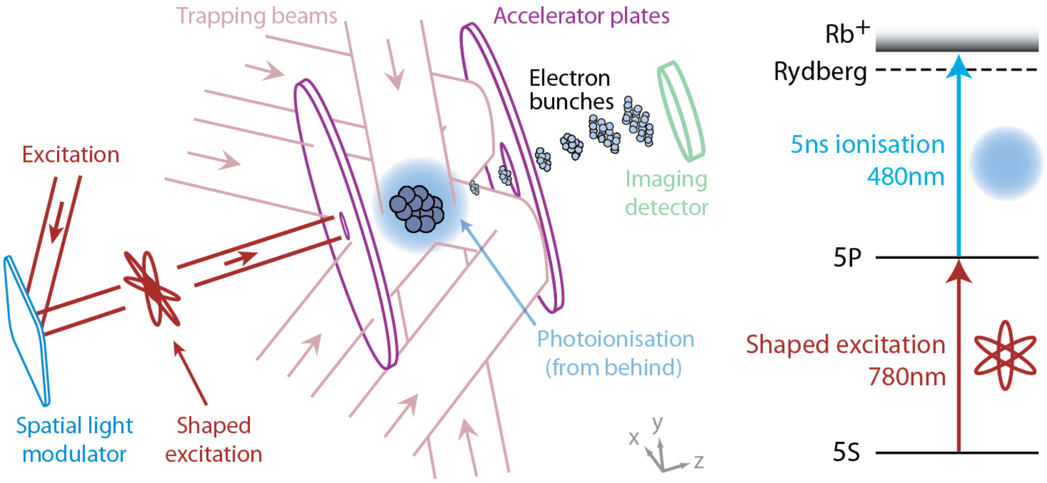

Figure 1 Experimental Schematic: Laser cooled and trapped atoms are photoionized with a combination of a 780 nm laser beam shaped by a spatial light modulator, and a 480 nm laser pulse with uniform intensity or shaped profile. Electrons and ions produced in the region of overlap between atoms, excitation, and photoionisation beams propagate to an imaging detector.

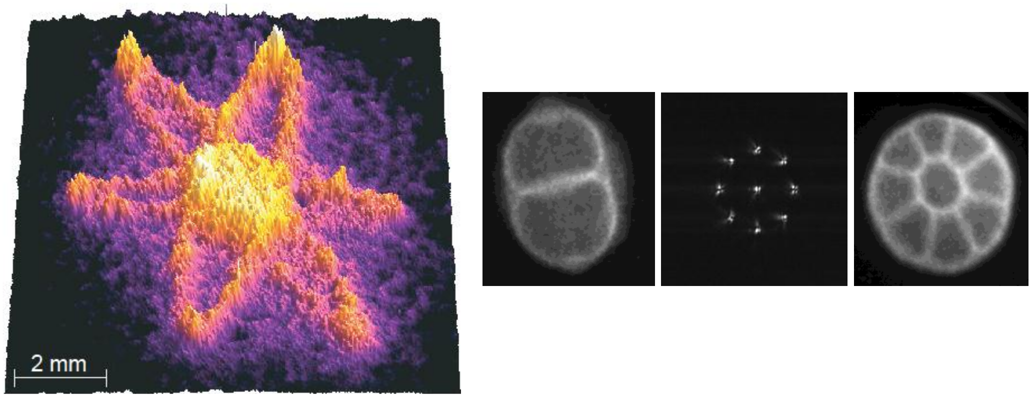

Figure 2 Cold Bunches: (a) A bunch of electrons (left) has been produced with a complex spatial distribution, and because of the low electron temperature (about 10 K) the bunch has retained its shape after propagating 24cm. (b) Images of propagated ion bunches (right) show two adjacent expanding ion bunches; excitation laser beam intensity profile for an array of mini-ion-bunches, and far right, the array of mini-bunches after propagation.

Cold Free Electron Bunches from Cold Atoms trapped in an AC-MOT

Matthew Harvey, Andrew J. Murray and Swapan Chattopadhyay

University of Manchester and Cockcroft Institute

A new cold electron source is currently under development at the University of Manchester in collaboration with the Cockcroft Institute. We anticipate that this new source will have applications in diffraction imaging, such as Low Energy Electron Diffraction (LEED) studies of surface structures, and for new compact LINACs, such as a laser wakefield accelerator being designed at the Cockcroft Institute.

This cold electron source will use a high density ensemble of laser-cooled ^{85}Rb atoms held in a new type of trap invented in Manchester, the alternating current magneto-optical trap (AC-MOT). The AC-MOT allows precise control of low energy electron interactions with trapped atoms, by eliminating all magnetic fields at the time of the interaction. This technique allows the experiments to proceed >300 times faster than with conventional traps. A pulsed cold electron beam will be produced by selective near threshold photo-ionization of the cold atom ensemble using high resolution lasers, followed by electro-static extraction and focusing into a beam.

The cold atom source will consist of a collimated beam of rubidium emitted from an oven which feeds a Zeeman slower stage that rapidly loads a storage MOT. From here, atoms will be transferred to a µ-metal shielded interaction chamber containing the AC-MOT. The interaction chamber will also contain a low energy electron spectrometer to allow the resolution and flux of the electron beam to be optimised. This will be done by measuring negative ion resonances in the elastic scattering from He, Ne and Ar, since these resonances appear as sharp structures in the elastic cross-sections.

This presentation will provide a description of the new experiment, including details of the AC-MOT.

Gerard van Veen, Program manager at FEI Company, FEI Company, Achtseweg Noord 5, 5651GG Eindhoven, PAYS-BAS

“ To be announced ”

GaAs Photo-Cathodes as Sources for Low-Velocity Electron Cooler Beams

C. Krantz [1], D. A. Orlov [1], A. Shornikov [1], A. S. Terekhov [2], A. Wolf [1]

[1] Max Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany
[2] Institute of Semiconductor Physics, 630090 Novosibirsk, Russia

Photo-excited III/V semiconductors can be close-to-ideal sources of cold, continuous high-density electron beams. Since 2006, the experimental electron cooler of the Heidelberg TSR storage ring is operated using Negative Electron Affinity (NEA) emitters based on GaAs photo cathodes. Electron beam temperature is a crucial parameter for efficient application of an electron cooler in the context of singly-charged heavy ions. The low transverse electron beam temperature (~10 K) of our set-up has paved the way to strong electron cooling of slow (~0.01 c) molecular ion beams in a storage ring. The future electron cooler of the Cryogenic Storage Ring (CSR), presently in construction in Heidelberg, will be based on the same emitter cathode and will reduce the low-energy limit of the electron cooling technique even further, designed to operate at electron beam kinetic energies down to 1 eV. We give an overview of present and future applications of photo-cathode electron emitters in merged-beam experiments with atomic or molecular ions.

Electron Source Needs for Dynamic Transmission Electron Microscopy

Bryan W. Reed, Thomas LaGrange, Joseph T. McKeown, Melissa K. Santala, and Geoffrey H. Campbell

Physical and Life Sciences Directorate, Lawrence Livermore National Laboratory
Livermore, CA 94551, USA

Single-shot dynamic transmission electron microscopy (DTEM), which demands sufficient current density to capture a complete image or diffraction pattern in a single short exposure, presents unique technical challenges. The stringent requirements of real-space imaging on the nanosecond time scale demand a source with high current, high brightness, and a time-independent transverse phase-space profile. The performance can be expressed in terms of a dimensionless figure of merit, the coherent fluence, which is nearly invariant in a well-designed electron optical column. If the coherent fluence is poor at the source, then no amount of electron-optical engineering can rescue the performance. Because of this, the ultracold beam concept is an extremely promising avenue for the improvement of DTEM performance. Still, a high coherent fluence does not guarantee high performance of the entire system. The electron column needs to be properly engineered to minimize the effects of electron-electron interactions both before and after the sample. It remains an open question whether atomic-resolution electron microscopy will be possible with picosecond-scale single exposure times, but one thing is certain: It will not be possible if these very challenging issues are not addressed.

Work was performed at LLNL under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering.

MOTIS: A Magneto-optical trap-based cold ion source

Jabez J. McClelland,[1] Brenton Knuffman,[1,2] and Adam V. Steele[1,2]
[1]*Center for Nanoscale Science and Technology, National Institute of Standards and Technology*
Gaithersburg, MD 20899 USA
[2]*Maryland NanoCenter, University of Maryland, College Park, MD 20742 USA*

We report on the demonstration of an ion microscopy system based on a magneto-optical trap ion source (MOTIS). Laser-cooled neutral atoms are trapped in a magneto-optical trap and cooled to a temperature of a few hundred microkelvin. An ionization laser tuned very close to threshold creates ions, which are accelerated by an electric field into a beam. The emittance of the beam, determined by the size of the source and the temperature of the ions, is extremely small, as a result of the ions' low temperature. This small emittance, together with a very low inherent energy spread in the beam, opens the possibility for creation of nanometer-scale focal spots.

Our microscopy system uses lithium atoms, which are cooled and trapped with diode laser light at 671 nm and ionized at 350 nm. The ion source is mated to a commercial focused ion beam system originally designed for use with a gallium liquid metal ion source. We have successfully demonstrated 2 keV ion beams with currents ranging from a few picoamperes to as high as 60 pA, and focal spot sizes as small as 27 nm (25%-75% width).[1] We will show examples of images taken with the microscope, and also discuss a number of interesting applications of nanoscale lithium implantation.

The demonstration of a lithium MOTIS as a viable microscopy tool represents a major step forward in the implementation of cold ion sources for focused ion beam applications. The ever-increasing number of atomic species that can be laser cooled and trapped (over 22 at present) suggests a great many new applications, including heavy-ion milling, low-damage light-ion microscopy, and species-specific nanoscale implantation. The low energy spreads inherent to the MOTIS make possible focused ion beams with unprecedented low energy, opening up new contrast mechanisms for imaging, as well as applications in precision milling depth control and ultra-low-damage milling.

[1] B. Knuffman, A. V. Steele, J. Orloff, and J. J. McClelland, New Journal of Physics **13**, 103035 (2011).

LASER COOLED CESIUM ATOMS AS A FOCUSED ION BEAM SOURCE

Leïla Kime, Orsay Physics 95 avenue des Monts Auréliens, Fuveau, France

FIB (Focused Ion Beam) technology is an essential tool in many fields such as semi-conductors industry. It can produce an ion beam with an adjustable diameter (down to 2.5 nm resolution).

Nowadays, FIB technology is based on the LMIS (Liquid Metal Ion Source) system mainly using the gallium ion. However, the gallium element shows some drawbacks such as large energy dispersion in the beam and sample contamination.

Looking for new ion sources is necessary to reduce these disadvantages and improve the performances. Thus, we proposed to elaborate an ion source based on ultracold plasma from an atomic beam. The ions will be produced through an original scheme using the ionization of Rydberg atoms created near ionization threshold. We expect this ionic beam to be more monochromatic and with a larger brilliance at a given energy. Cesium element has been chosen because of his non contaminating characteristics and for its reactivity useful in analysis.

This new ion cesium source is developed in Orsay Physics with the collaboration of his academic partner Aime Cotton Laboratory.

This presentation will describe the theoretical and experimental principal of the actual status of this new source.

Ultracold Ion Beams

Edgar Vredenbregt, Eindhoven University of Technology

Near-threshold photo-ionization of laser-cooled atoms provides a new class of ion sources. Characteristic of such sources is an extended source size combined with low angular spread. Whether ultracold sources are viable alternatives for, e.g., the Liquid-Metal Ion source depends on achieving operation at high brightness, low energy spread and/or with alternate ion species that can enable new applications. A number of these properties have already been investigated and some will be reviewed in the talk. Brightness achieved so far is well below that of the LMI and alternatives using laser-cooled atomic beams rather than traps are therefore being investigated. While these promise better performance on paper, disorder-induced heating and technical realization are challenges to overcome.

Cs^+ ions produced out of a laser cooled atom beam

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E. Arimondo[1,2], M. Allegrini[1,2], F. Fuso[1,2,*]

[1.] *Dipartimento di Fisica Enrico Fermi and CNISM, Università di Pisa, 56127 Pisa, Italy*
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Abstract: A simple two-photon two-color, one resonant, scheme is applied to photoionize Cs atoms belonging to a "slow and cold" atom beam produced out of a pyramidal Magneto-Optical Trap (MOT). The ion yield is analyzed as a function of the experimental parameters by a charge detector. Results acquired so far demonstrate that the specific sub-thermal properties of the atom beam strongly affect the ion dynamics, in particular its monochromatic character.

There is presently a great interest in the exploitation of laser manipulation techniques for the production of charged particle beams with superior dynamical properties [1]. The scientific and technical efforts devoted to this aim could bring great advantages to all the range of technologies presently using charged particles. For instance, Focused Ion Beam (FIB), a mature technology which is experiencing a revamped huge interest for material modification and imaging at the nano-scale, would strongly benefit from the availability of monochromatic ion beams, able to overcome the present limitations in tight focusing due to chromatic aberrations in the electron-optics stage [2].

Different approaches can be deployed to use laser manipulation in such a context. We are exploring the possibility to transfer to the charged particle beams the peculiar dynamics achieved in a continuous Cesium atom beam produced out of a pyramidal-Magneto Optical Trap (MOT) [3], already used for atomic nanofabrication [4]. Such a beam, while featuring a density not sufficient for immediate industrial applications (typical flux ~ 10^9 at/s), offers remarkable dynamical features such as, strong collimation, achieved through a 2D optical molasses stage, and small longitudinal velocity. In the presently running setup, completely re-arranged and re-designed in view of photoionization, a residual divergence < 8 mrad and a longitudinal velocity ~ 12 m/s are obtained, motivating the definitions of "cold and slow" for the beam. Moreover, the width of the longitudinal velocity distribution is roughly 1/10 its average value, ensuring a remarkable relative monochromatic character.

In the present development stage of the experiment, aimed to a preliminary assessment of the approach, the simplest possible photoionization scheme is used: two laser beams crosses the atoms at orthogonal direction, one resonant with an hyperfine transition of the $6^2P_{3/2}$ state at around 850 nm, and the other one at 405 nm, producing ionization at ~ 0.6 eV above threshold. Measurements are carried out with a charge detector which can be mounted either parallel or orthogonal to the atom beam axis.

Several parameters are examined including the ion yield as a function of the experimental conditions, in particular of the power and frequency of the laser exciting the atoms to the $6^2P_{3/2}$ state, and the kinetic energy of the ions. To this aim, the ionizing laser is pulsed by an Acousto-Optic Modulator (AOM) and time-of-flight measurements are performed. Simulation of the electrostatic field used for guiding the charges to the detector allows interpreting the results, which lead to a monochromatic degree $<\Delta E_{K,long}>/<E_{K,long}>$ ~ 1/10, similar to the values measured in the starting atom beam. Such value, which is already competitive with the present technological implementations, turns limited by the electrostatic field homogeneity in the interaction region, resulting in a non homogeneous charge acceleration.

Further work is planned oriented towards several objectives. A complete characterization of the ion beam will be carried out, including determination of the transverse properties, and a specifically designed charge extraction stage will be implemented to further improve the monochromatic character of the beam. Moreover, laser manipulation techniques will be developed aimed to on-demand production of ion packets with pre-defined, engineered, dynamical features. Within this context, the relatively small particle flux of the setup, leading to a continuous ion current < 1 pA, will not be detrimental, since advanced applications like precise doping or single ion interaction with solid surfaces do not require large particle density.

Acknowledgements: work supported by FP7-MC-PEOPLE-IAPP Project 251391 “COLDBEAMS”.

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The Liquid Metal Ion Source – A Brief Introduction

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Abstract

The liquid metal ion source (LMIS) is an extremely important ion source technologically. In an appropriately designed optical column the small virtual source size and the relatively high angular intensity of the LMIS allows an ion beam to be focused to a spot as small as ≈ 5 nm (FWHM) containing 1 – 10 pA current, producing a current density $J \sim 10$ A cm^{-2}. When used as a sputtering or machining tool, material can be removed from a surface at a rate of the order of 1 μm^3 per nA of ion current, depending on the ion species used and the material being sputtered. Ion beams produced by LMIS-based focused beam systems have proved to be of enormous importance to the semiconductor industry, allowing failure analysis and circuit editing functions to be performed on a ~ 10 nm scale. This has made the LMIS an important enabling technology. As well, it has proved to be of great value for materials research in general.

A LMIS consists of a blunt field emitter substrate coated with a liquid metal having suitable properties, two of the most important being adequate surface tension so the liquid can survive exposure to an intense electric field without disintegrating, and vapor pressure at the melting point low enough that the liquid will last a reasonable time at normal ion currents. When an electric potential of sufficient magnitude is applied to the liquid metal the liquid deforms into a conical shape under the opposing forces of electrostatic field stress and surface tension. As the metal approaches a conical shape the field strength at the apex of the cone becomes high enough to support field evaporation followed by ionization; ions are then accelerated rapidly away from the cone apex by the high field. The flow of the liquid metal that replenishes the material lost by ionization results in a further deformation of the liquid into an elongated jet near the cone apex. At low total emission currents (1 - 2 μA) the source has very useful ion optical properties including a small virtual source size ≈ 50 nm, corresponding to an emittance $\varepsilon_x = \varepsilon_y \approx 5 \times 10^{-7}$ m rad $V^{1/2}$, an angular intensity of ≈ 20 μA sr^{-1}, and a reasonable energy spread ≈ 5 eV. Focused beam currents of 1 pA - 50 nA are routinely achieved. In consideration of the forces involved and the high rate of flow of the liquid metal, the source is remarkably stable: the noise in the ion beam is only ≈ 2X the shot-noise level. Unlike an electron field emitter, the virtual or apparent source size is much larger than the physical source size because of space charge effects (statistical beam broadening). The current density just above the emitting area is ~ 10^6 A cm^{-2}, as the diameter of the region where ion emission takes place is ~ 5 nm. With a proper source configuration the LMIS is capable of long life (~ 1500 μA-hours for Ga metal).

FIB : current and future

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iFib

incredible focused ion beams

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We will present someFIB based techniques for the local synthesis of nanostructures such as nanowires, -sheets and -webs.

Based on the idea of a catalytic approach, antimony nanowires were grown with diameters of about 20 nm and lengths of a few micrometers.
Therefore an intense focused Ga ion beam was used to form catalytic nanoparticles alloyed by the constituents of the growing nanowire in situ, eliminating the usual requirement of pre-patterning quantum sized catalyst droplets. These FIB generated Sb nanowires were integrated in humidity sensors as well as a CMOS compatible pH sensor.
These above studies illustrate the potential of this approach for synthesis of nanowires in room temperature ambient without using a gas-type source. We emphasize that our approach should not be limited solely to the materials discussed here – other sources of the ion beam as well as heating of the sample during FIB processing should extend this method to other materials thereby opening the door to cheaper and faster commercialization and being compatible with on-chip microelectronics.

Furthermore we present an approach for Fib synthesis of free-standing graphite nanosheets with a thickness of about 40 nmoriented parallel to the scanning Fib. At a substrate temperature of 600°C a self assembled free standing carbon nanosheet was formed.An SEM video shows the assembling of this carbon nanosheet in situ and in real-time. Such carbon nanosheets appears to by crystalline and shows effective photoluminescence at telecommunication wavelength.

Finally we present an approach for Fib induced synthesis of free-standing Ge nano-webs with a thickness down to 20nm and luminescence in the near-infrared region. FIB exposure of Ge and subsequent annealing in a rapid thermal processing system leads to the formation of Ge nanowebs. The resulting pattern were investigated by SEM, SIMS and AFM imaging. The photoluminescence- and raman-properties of the resulting structures were investigated with a WITec alpha300 and an excitation wavelength of 532nm.

Focused Ion Beams : A tool for Nanomachining and Advanced Transmission Electron Microscopy

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Focused ion beams have been since several decades a flexible tool for material modifications and analysis. Micro and Nano Electronics were the first industrial environment to take advantage of direct writing capabilities of FIB. The coupling of FIB and SEM has provided a unique tool for in-situ, real time and high resolution surface modifications. Moreover, Gas Injection Systems added submicrometer deposition capabilities and enlarged the application spectra of FIB. Finally micromanipulators ended to transform these systems in real nanofactories for material science.

Recent progress in transmission electron microcopy (HREM, Holography, Electron Energy loss Spectroscopy, Dynamic Imaging...) due mainly to aberration correctors are demanding for new high quality TEM preparation with new constraints in term of thickness, point/extended defects and planarity. With new developments in this field focused Ion beams can be an answer to these new needs.

A high brightness ion source by laser-cooling an atomic beam

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A new type of high-brightness ion source is under development which employs transverse laser cooling and compression of a thermal atomic Rb followed by photo-ionization. The source should be compact enough to fit on an existing Focused Ion Beam instrument. Simulations of a 10 cm long cooling stage and of disorder-induced heating of the resulting ion beam, predict an achievable brightness for $^{87}Rb^{+}$ of order 10^{7} A/m^{2} sr eV at an energy spread of less than 1 eV and a current of tens of pA, which is substantially better than conventional ion sources. Experimental realization of the compact ion source has recently started with the development of an efficient high-flux atom source.

A particle beam for nanotechnological purposes obtained through laser manipulation of Cs atoms

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Abstract: By using laser cooling and trapping methods, we have developed a Cs beam with specific dynamical properties. Besides its original application, intended for atom nanofabrication, the high degree of collimation and the slow longitudinal velocity of the atoms make the beam an excellent tool to investigate spectroscopy features and a candidate as the particle source for producing an ion beam with sub-thermal properties through atom photoionization.

Since the early introduction of laser cooling, efforts have been devoted to find technological applications to the newly developed techniques. A strong driving force has been the quest for miniaturization, rapidly growing in the last decades. Within this frame, the ability owned by laser manipulation to tailor the dynamical properties of atoms in the vapor state is a key element that, when properly implemented, can lead to unprecedented levels of control in atom position and speed. A vivid example of the technologically-oriented efforts is represented by atom lithography [1], also known as Atomic Nano-Fabrication (ANF [2]). In such an approach, the accurate control of the atom dynamics led to surface structuring in the tens of nanometers range at a time when industrial lithography could barely reach the 60-90 nm limit. The strong improvements in spatial resolution experienced by the conventional technology made interest towards ANF to drop rapidly. However, new and challenging areas of technological exploitation have recently shown up.

Among others, a great interest has grown around the use of laser cooling tools in the production of ion beams with superior dynamical properties, able to overcome the present limitations in the field of Focused ion Beam (FIB) technology. In particular, precise manipulation of the particle dynamics can lead to strongly monochromatic beams, virtually free of chromatic aberration effects. To explore such a possibility, we have used a laser cooled Cesium beam, originally conceived for ANF [3], as the primary source for the realization of a continuous ion beam through photoionization.

The atom beam is produced out of a pyramidal Magneto-Optical Trap (MOT) [4], a configuration of mirrors and prisms arranged into the shape of a hollow pyramid with reflecting walls and an apical hole 1x2 mm^2 wide. A pair of coils is wounded around the pyramid, connected in the anti-Helmoltz configuration in order to produce zero magnetic field on the pyramid axis. A single laser beam quasi-resonant with the F=4 → F'=5 hyperfine transition to the $6^2P_{3/2}$ state illuminates the pyramid, leading to a configuration similar to that of standard MOTs but for the axial unbalance in radiation pressure, due to the missing reflection from the pyramid apex. In these conditions, a continuous flow of atoms leaves the apical hole and crosses a 2-D optical molasses region intended to transversally cool the atoms, hence to reduce the beam divergence.

A specific region of the vacuum chamber, equipped with optical windows, allows for spectroscopic characterization of the beam. Absorption spectroscopy dictates a typical peak particle density around 8x10^7 at/cm^3, essentially limited by the background Cs pressure (produced by atom dispensers) and by the available laser power (< 100 mW). Fluorescence imaging in the interaction region gives size and divergence of the beam, which are 4x6 mm^2 (fwhm) and 7 mrad (full divergence angle), the latter indicating a transverse kinetic temperature of the beam in the hundred of μK range. The average longitudinal velocity of the atoms, measured by optical time-of-flight techniques, is 12 m/s; a best fit of the velocity distribution according to a translated Maxwellian gives a distribution width ~ 1.4 m/s. The ratio between the width and the average value of the velocity, markedly smaller than for effusive beams, well illustrates the sub-thermal character of the beam.

Atom ionization, accomplished with a simple two-photon two-color, one resonant, scheme, leads to a ion yield on the order of 10^6 ion/s, in agreement with the ionization cross section and substantially limited by the small intensity available for the ionizing process (laser diode at 405 nm, 20 mW, unfocused). In the conditions of the experiment, the ion current is linearly proportional to the population of the atomic excited state. The availability of a sensitive and non obtrusive detection method such as the charge detector mounted in the vacuum chamber, allows us to investigate the population of the $6^2P_{3/2}$ state as a function of the experimental parameters (laser frequency and power). Thanks to the small velocity of the atoms and the subsequent long interaction times with the laser beams, optical pumping phenomena become extremely relevant. A comprehensive investigation of the pumping effects for all the accessible hyperfine levels is carried out and the results interpreted on the basis of numerical simulations of the laser/atom interaction processes in the actual experimental conditions.

Along with their interest from the fundamental point of view, results can have applicative outcomes in designing selective excitation and ionization pathways aimed at realizing on-demand delivery of ion bunches with pre-defined dynamical properties, which could have applications in a range of emerging techniques such as, precise doping of materials, space-controlled decoration of surfaces, nanosized milling.

Acknowledgements: work supported by FP7-MC-PEOPLE-IAPP Project 251391 “COLDBEAMS”.

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Focused Ion Beam Implantation of Li^+ in WO_3 Using A Magneto-Optical Trap Ion Source

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We report on nanoscale implantation of lithium ions using a focused ion beam based on a magneto-optical trap ion source (MOTIS). At a low beam energy of 2 keV, this system has demonstrated a focal spot of 27 nm and a current of approximately 1 pA using Li^+ ions,[1] a level of performance not seen with other ion sources. This capability introduces opportunities for implanting optically and/or electrically active ions into materials with nanoscale precision. Such spatially-controlled implantation suggests new prospects for optical and electrical device fabrication and also enables detailed studies of dopant diffusion in various materials.

As a demonstration, we have conducted a series of experiments implanting Li^+ in WO_3. Li^+ ions produce an electrochromic effect in WO_3, changing its optical properties dramatically and altering its conductivity.[2] Using focused ion beam pattern generation software, we implanted Li^+ in 35 nm thick amorphous WO_3 films. The resulting implantations were examined optically by illuminating with light at a wavelength of 750 nm and observing in an optical microscope. Clear patterns were seen, corresponding to increased absorption where Li^+ was implanted. For electrical measurements, Li^+ was implanted across gold/titanium electrodes patterned on the WO_3 film. I-V curves were measured, showing increased conductivity of the junctions as a result of the ion implantation.

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LASER COOLED CESIUM ATOMS AS A FOCUSED ION BEAM SOURCE

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FIB (Focused Ion Beam) technology is an essential tool in many fields such as semi-conductors industry. It can produce an ion beam with an adjustable diameter (down to 2.5 nm resolution).

Nowadays, FIB technology is based on the LMIS (Liquid Metal Ion Source) system mainly using the gallium ion. However, the gallium element shows some drawbacks such as large energy dispersion in the beam and sample contamination.

Looking for new ion sources is necessary to reduce these disadvantages and improve the performances. Thus, we proposed to elaborate an ion source based on ultracold plasma from an atomic beam. The ions will be produced through an original scheme using the ionization of Rydberg atoms created near ionization threshold. We expect this ionic beam to be more monochromatic and with a larger brilliance at a given energy. Cesium element has been chosen because of his non contaminating characteristics and for its reactivity useful in analysis.

This new ion cesium source is developed in Orsay Physics with the collaboration of his academic partner Aime Cotton Laboratory. This presentation will describe the theoretical and experimental principal of the actual status of this new source.

Measurements on a new laser-cooled ion source

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We report on a new ion source created by photoionizing a cold, dense beam of atoms. This source is capable of forming a high brightness, low energy spread ion beam which is well suited to nanoscale focused ion beam applications.

The apparatus consists of a laser-cooled beam of cesium atoms photoionized on a two-photon transition in a crossed laser beam geometry between two electrodes. We report measurements of the ion beam current and atomic beam temperature, the predicted effects of inter-ion Coulomb interactions using Monte Carlo simulations, and provide a model of the ionization volume geometry. Together with the performed measurements, this model enables an estimation of the brightness and energy spread achieved to date in this new ion source.

Study of a low energyelectron source based on a cold atomic beam.

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We present here our experiment to produce a low energy electron beam with high brightness. This is done by using a cold atom source and ionizesthe beam.

Our experiment is based on a 2D-MOT. We cool Cs atoms in 2 dimensions. On the last dimension we apply a pushing beam to accelerate the atoms in a specific direction and create a continuous atomic beam with a high flux near 10^{10} atoms per second. With this flux, it is possible to create ~1 nA electron beams. A study on the power, the shape and the wavelength of the pushing beam has been achieved to control the flux of atoms in the ionization area. Permanents magnets can also be added to create a magnetic field gradient and compress the atomic beam and control the flux of atoms in the ionization area.

We shall then study the ionization of the atoms and how to focalize them on small surface while restricting the energy scattering. Simulations with General Particle Tracer (GPT) software have been performed, while changing the current of the electron beam, the initial position of the electrons and the paraxial aberrations, to know what minimum area can be achieved with our apparatus. One important result is that with our experiment, we should have an electron beam 1000 times better in terms of current density and of focusing size.

The General Particle Tracer (GPT) code

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Over the past years our General Particle Tracer (GPT) package has become a well established simulation tool for the design of accelerators and beam lines. GPT is a 3D code that tracks charged particles through any electromagnetic field, including electrostatic, magnetostatic and time-dependent radio-frequency fields. Simulation time is kept to a minimum with a multi-core 5th order Runge-Kutta tracking engine with adaptive stepsize control. The GPT code has the ability to efficiently calculate all pair-wise interactions from first principles in O(N log N) CPU time. This feature makes it an ideal candidate for the design and understanding of sources where disorder induced heating is the dominant mechanism degrading beam quality. A description of the internal algorithms of GPT and a selection of sample applications will be presented.

Poster Title: Towards reversal of space charge expansion using a cold atom electron source

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Abstract: The ability to generate and control the shape of an arbitrary electron bunch in three dimensions and in real time has been established with a Cold Atom Electron Source (CAES) at The University of Melbourne. Thus, experimentally realising uniform density ellipsoidal electron bunches is possible with this system. These bunches are desirable due to their expansion being linear under self-field effects. With electron diffraction experiments in mind, reversal of this space charge expansion due to Coulomb repulsion can then be achieved by conventional electron optics, allowing the maximum possible brightness to be incident upon a target. This poster showcases some of the work currently ongoing with our CAES, addressing the space charge problem, uniform density bunches and a crossed dipole trap.

Towards the Realization of a rare gas ion source

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One of the major challenges for the Focused Ion Beam (FIB) community is to dispose of a rare gas ion beam. In standard FIB, the source is a liquid-metal ion source (LMIS). It typically employs gallium, for its high surface tension and low vapor pressure, but with the major drawback that contamination of the treated surfaces by Ga^+ is inevitable. There are several efforts to develop non-contaminant (noble gas) ion sources instead of LMIS but, up to now, none of them have met the minimum requirements in terms of flux, spot size, stability, and brightness. A rare gas source would thus be a major innovation for the FIB community.

We choose to use an existing "cold molecules" experiment at CNRS to start this project. We have already realized an operating rare gas beam machine and an operating metastable rare gas beam machine, but not exactly in the ideal conditions (argon rare gas pulsed beam and not continuous beam). However an original (Sisyphus) transversal cooling and compression of the beam is foreseen. We thus believe to be on time for the characterization of the high flux, transversally cooled rare gas beam.

The steps are the following :

1) Realization of an effusive rare gas beam

2) Optimization of the metastable atoms formation

3) Transversal cooling and compression of the beam

4) Ionization of the beam. Characterization of the ion source

5) Realization of the FIB column coupled to the ion source, coupling of the rare gas ion source to the FIB and Final test of performances of the rare gas FIB. Finally, the realization of a commercial prototype of a Ar FIB.

Ultrafast and ultracold electrons with polarization effects

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We experimentally investigate the properties of electron pulses extracted from trapped rubidium atoms by near-threshold photoionization using nanosecond tunable dye lasers and femtosecond lasers combined with an OPA. We find that the polarization of the ionization laser has a major influence on the achievable transverse electron temperature, which in turn determines the intrinsic coherence length of the source. Also, we show that few-Kelvin electron temperatures can be achieved with ultrafast lasers despite the spread in photon energy, which at first sight violates Heisenberg's time-energy uncertainty principle. We discuss how these observations can be understood from a classical model of the photo-ionization process in an ambient electric field, which among others leads to a reduction of the transverse velocity spread of electrons compared to field-free ionization. The model also predicts achievable pulse lengths, and we propose an experiment to determine the resulting multiple-pulse structure using a radio-frequency streak cavity.

“Making the Molecular Movie”: First Frames……Now with REGAE Musik

R. J. Dwayne Miller
Max Planck Group for Atomically Resolved Dynamics,
Department of Physics, University of Hamburg,
The Centre for Free Electron Laser Science, DESY and
Departments of Chemistry and Physics
University of Toronto

One of the great dream experiments in Science is to watch atomic motions as they occur during structural changes. In the fields of chemistry and biology, this prospect provides a direct observation of the very essence of chemistry and the central unifying concept of transition states in structural transitions. From a physics perspective, this capability would enable observation of rarefied states of matter at an atomic level of inspection, with similar important consequences for understanding non-equilibrium dynamics and collective phenomena. This experiment has been referred to as "making the molecular movie". Due to the extraordinary requirements for simultaneous spatial and temporal resolution, it was thought to be an impossible quest and has been previously discussed in the context of the purest form of a gedanken experiment. With the recent development of femtosecond electron pulses with sufficient number density to execute single shot structure determinations, this experiment has been finally realized (Siwick et al. Science 2003). Previously thought intractable problems in attaining sufficient brightness and spatial resolution, with respect to the inherent electron-electron repulsion or space charge broadening, has been solved. With this new level of acuity in observing structural dynamics, there have been many surprises and this will be an underlying theme. Several movies depicting atomic motions during passage through structural transitions relevant to condensed phase dynamics will be shown (Sciaini et al. Nature, 2009, Ernstorfer et al. Science 2009, Eichberger et al Nature 2010, Jean-Ruel, J Phys. Chem. A 2011). The primitive origin of molecular cooperativity has also been discovered in recent studies of molecular crystals. These new developments will be discussed in the context of developing the necessary technology to directly observe the structure-function correlation in biomolecules — the fundamental molecular basis of biological systems.

The future is even brighter with the advent of a new concept in relativistic electron guns that will open up direct observation of atomic motions in solution phase to gas phase systems with 10 femtosecond time resolution to watch even the fastest atomic motions. Some of the important scientific problems to be addressed with ultrabright electron sources will be discussed to give an impression of the potential impact of this emerging field.

Electron microscopy resolved in space, energie and time

Fabrizio Carbone

Ecole Polytechnique Federale de Lausanne (EPFL)

In this seminar, the recent developments in ultrafast electron microscopy will be discussed. The design and implementation of a new fs-resolved TEM will be discussed, demonstrating the ability to obtain high coherence, spatial, energy and time resolution by careful engineering of the gun elements. The gun elements of our JEOL JEM2100 are modified to accomodate an alluminum mirror used to stirr the beam towards the LaB6 photocathode. Also, a C0 lens is added immediately after the gun section of the TEM. This extra lens has the purpose of collecting as many photoemitted electrons as possible when operating with low currents in time-resolved mode. We show that these modifications do not affect the performances of the TEM in conventional static operation. The spatial resolution was tested on a gold nanoparticle obtaining clear lattice fringes. Furthermore, the addition of the C0 lense is shown to imrpove the energy resolution in EELS, because it allows to operate with a lower current in the filament, thus reducing space charge effects, while preserving the birghtness of the beam. The potential of these techniques will be discussed via a series of examples including graphite thin films, nanotubes, and more recent results obtained on the charge density wave system TaS2.

The combination of time-resolved diffraction, imaging and EELS, provided an unprecendented understanding of the intimate relation between charges and ions in the photoinduced evolution of graphite films. The microscopic description of these phenomena will be presented and an overview for the future perspectives of these tools in condensed matter physics will be given.

Single-electron pulses for visualization of atomic and electronic motion

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Motions of atoms and electron densities in materials and molecules involve femtosecond and attosecond times, but also the three spatial dimensions on a sub-Angstrom scale. Our approach for a four-dimensional visualization is based on ultrafast diffraction with wave packets of single electrons [1]. This restricts the investigations to reversible processes, but totally avoids the space-charge effects that in conventional approaches limit the temporal resolution and ability to study complex materials. Our use of single electrons is motivated by the possibility to investigate the regime of electronic dynamics [2].

Tailored excitation of metallic photoelectron sources at photon energies close to the work function produces single-electron pulses with a minimized dispersion and divergence [1]. A microwave cavity can be used to further compress the single-electron wave packets in time [3], down to durations approaching one femtosecond. 'Isochronic' magnetic lenses [4] avoid the temporal distortions induced by the imaging system. The measured transverse coherence of the pulses exceeds 20 nm, enough to cover biomolecular systems with femtosecond and subatomic resolution. Electron densities can move in times as short as attoseconds. Our single-electron pulses afford some promise to reach into this novel regime [2]; we will discuss our approaches and what discoveries we may expect to see [5-6].

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Molecular Dynamics Simulations for Laser-Cooled Sources

Bas van der Geer, Eindhoven University of Technology, Pulsar Physics

Electron and ion sources based on laser-cooling and trapping techniques are a relatively new reality in the field of charge particle accelerators. The dynamics of these sources is governed by stochastic effects, and not by the usually dominant space-charge forces. This is the direct consequence of the extremely high initial phase-space density. Correct simulation results require a full molecular dynamics simulation, i.e. we need to track each and every particle including all pair-wise interactions. The two main candidates for such molecular dynamics simulations are the Fast Multipole Method (FMM) and the Barnes&Hut scheme (B&H). Tradeoffs are given, and simulation results for the B&H method implemented in the General Particle Tracer (GPT) code are presented for realistic test-cases.

FIB Assembly of Semiconductor Nanostructures for Potential Nanoelectronic Device Applications

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We have combined the short range processes of strain-induced self assembly with longer range lithographic forcing functions to create semiconductor nanostructures arrays that can be controlled over many orders of magnitude of length scales. This work uses the input of positional maps from controlled arrays of focused ion beam pulses to locally modify Si substrate surfaces. This “template” then controls the subsequent assembly of (Si)Ge nanostructure arrays through epitaxial growth. We examine how information is transferred from the original template maps into the observed distributions of nanostructures that result, and show that it is possible to accurately template nanostructure arrays over length scales ranging from nanometers to macroscopic dimensions. We also discuss mass-selected focused ion beam methods intended to deliver pulses of electronic or magnetic doping species with doses as small as a few ions per pulse and positional accuracy of order ten nm. With such methods we hope to functionalize ordered nanostructure arrays to develop prototype nanoelectronic devices based on motion of just a few units of electronic charge or spin. The requirements for ion species, energies, pulse length, and beam diameters will be discussed.

Work in collaboration with J. Floro (UVa), J. Gray (U. Pittsburgh), Frances Ross (IBM), M. Gherasimova (S. Connecticut State), A. Portavoce (CNRS), J. Graham (FEI,) P. Balasubramanian, S. W. Chee and J. Murphy (RPI).

Challenges and Opportunities - Focused Ion Beam Processing at the Nano-scale

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In this presentation we will present our work aiming to explore the nano-structuring potential of a highly focused pencil of ions. We will show that Focused Ion Beam technology (FIB) is capable of overcoming some basic limitations of current nano-fabrication techniques and to allow innovative patterning schemes for nanoscience. In this work, we will first detail the very high resolution FIB instrument we have developed specifically to meet nano-fabrication requirements. Then we will introduce and illustrate some new patterning schemes we propose for next generation FIB processing. These patterning schemes are (i) Nano-engraving of membranes as a template for nano-pores and nano-masks fabrication. (ii) Local defect injection for magnetic thin film direct patterning. (iii) Functionalization of graphite substrates to prepare 2D-organized arrays of clusters. (iv) Selective epitaxy of III-V semiconductors on FIB patterned surfaces.

Finally we will show that FIB patterning is fully compatible with “bottom-up” or “organization” processes.

We will conclude this presentation by introducing some emerging concepts and principles we have started to explore for next-generation FIB processing and systems.

Application of the Helium Ion Microscope

Vignesh Viswanathan, National University of Singapor

Room temperature ion source: various ion species, high brightness and low energy spread

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Keywords: Ion source, Ion beam, FIB

High brightness beams of Ga+ and He+ ions have made a tremendous impact in nano-fabrication and ion microscopy. The extension of the technology to beams of H^+, Xe+, Ar+, O_2+, etc. could enable new applications in the nano-scale. We have designed an ion source based on electron impact gas ionization inside a sub-micron sized gas chamber. The gas chamber consists of two very thin membranes (~100nm) separated by a small distance (100 to 1000nm) as shown in Figure 1. A small aperture (100 to several hundred nm in diameter) in each membrane allows electrons to enter and ions to exit while keeping a high gas pressure inside the gas chamber. A small bias (<1V) assists the ion extraction and effectively determines the energy spread of the ion beam. The gas chamber can be supplied with practically any gas species. Electron impact ionization does not require a high temperature, so operation is at room temperature.

Due to a high ionization rate resulting from a high input current density electron beam from a Schottky electron gun and a very small ionization volume, our source is expected to produce a reduced brightness matching or even exceeding that of typical Gallium LMIS [1]. Figure 2 shows the expected brightness as a function of the incident electron beam energy. The calculations are based on the current density that a typical Schottky electron gun can deliver, with typical source and lens specifications taken from ref. [2]. An electron probe size of about 100nm yields the highest current density at an electron energy of ~1keV [3]. Furthermore, the calculations take into account the energy dependence of the electron impact ionization cross sections of each gas. We have considered the regime in which Ion-atom interactions and coulomb interactions are negligible. Ion-atom interactions are negligible when the chamber spacing is smaller than the mean free path of the ions. For 100nm membrane spacing, this is the case up to almost 1 bar. Coulomb interactions can be ignored when the average time between the production of ions is much smaller than the average residential time of an ion in the chamber. We estimate that up to 2nA of ion current can be produced from a gas chamber with a 100nm spacing without much coulomb interactions.

In a proof-of-concept study, we produced ion beams of several different gas species from a prototype gas chamber using an electron beam inside a SEM. Using micro-channel plates and a phosphor screen, we successfully acquired ion beam patterns proving that our source indeed outputs a beam of ions. We then measured up to several 100's of pico-amperes of ion current in a Faraday cup using an input electron beam current of ~14nA with 1keV incident elecron energy. Measured exit ion current as a function of gas pressure for Helium, Argon, Xenon, and air is shown in Figure 2. The differences in the measured ion currents among the gases reflect the fact that each gas has a different electron impact ionization cross section for a given incident electron beam energy. The graph also clearly shows the deteriorating ion current at higher pressures indicating ion transmission rate dependence on the mean free path of gas particles inside the gas chamber.

Fig. 3 shows a measured energy spread spectrum of an argon ion beam produced from a prototype gas chamber with 2µm spacing and an 800nm double-aperture diameter. The pressure inside the gas chamber was kept at approximately 50mbar. The observed spectrum is a combination of the influence of the bias voltage and the E-field (~0.8V/um) created by the Ion accelerator penetrating into the gas chamber through the ion exit aperture. Changes in the bias voltage showed to be equal to changes in the energy spread. At the same time, changing the bias voltage influenced the total ion current because of the lens effect of the bias voltage.

Progress has been made in reducing the gas chamber dimensions down to 200nm chamber spacing and 100nm aperture size. Furthermore, we are working on implementing the source into a commercial focused ion beam instrument (FEI dual beam). It allows us to fully characterize the source properties and to explore the applications of the newly available high resolution ion beam species.

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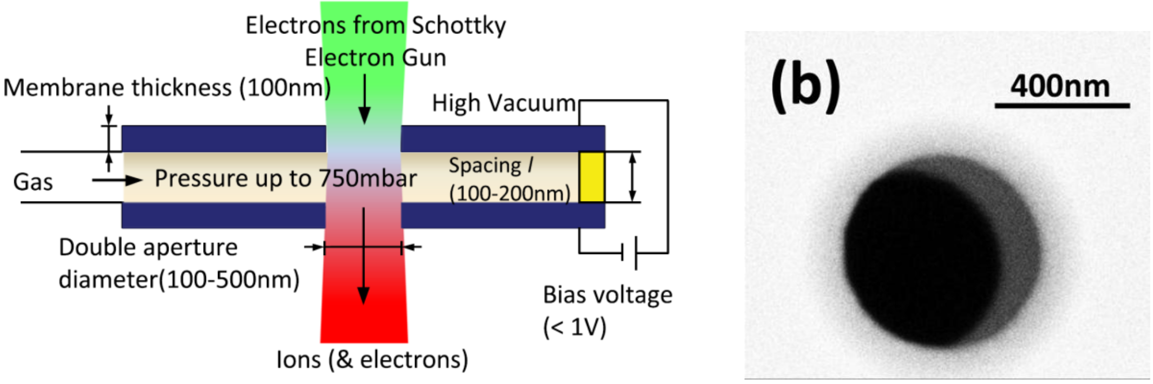

Figure 1. *Left: The essential element of the novel ion source; a sub-micron sized gas chamber with a top aperture in which electrons enter and a bottom aperture for extracting the ions. A small bias (<1 V)is applied to extract the ions. Right: a SEM image of the FIB milled apertures slightly tilted to show the two membranes.*

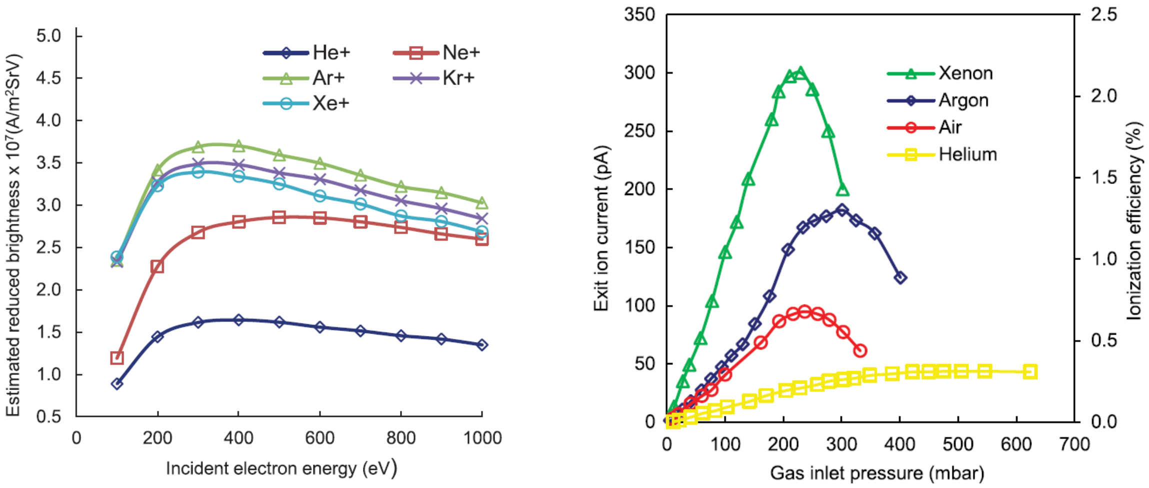

Figure 2. *Left: Predicted reduced brightness of the ion beam based on the characteristics of a typical Schottky electron source and electron impact ionization cross sections. Right: First result of a measured ion current of four gas species. An input electron probe current of 14 nA and 1 keV beam energy was used. Gas chamber spacing = 2.3 um, aperture diameter 1.5 µm.*

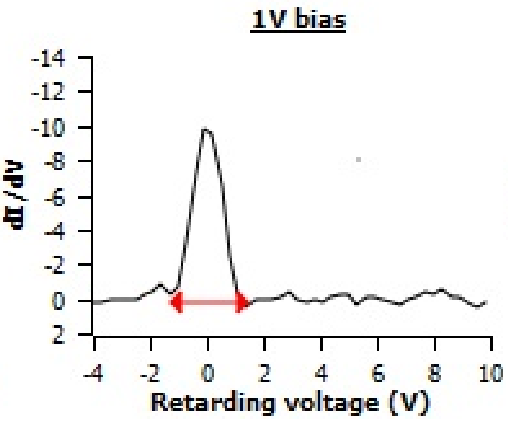

Figure 3. *Energy distribution function of extracted ion beams measured in a retarding field analyzer.*

Poster Session Tuesday 2 October 2012

The program of this Poster Session is exactly the same as the Poster Session of Monday. So please, see at Monday 1st October to the program of this session.

Electron and X ray Beam with Laser-plasma accelerators.

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The hundreds GV/m longitudinal electric fields produced in laser plasmas can be used to generate, in a compact and reproducible way, energetic electron beams with tuneable parameters. In those laser plasma accelerators, different injection schemes have been demonstrated such as the forced laser wake field [1], the bubble/blow out regime [2], or the colliding laser pulses [3] that offers the possibility to control the electron beam parameters. These electron beams with peak current of a few kA [4] are of interest for a very broad range of applications in medical, biological, chemistry or material science domains [5]. They are also of major interest for the production of very bright X/gamma ray beams [6]. I report here on the evolution of laser plasma accelerators developed at LOA and on very recent achievements we performed on the applications side.

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Time-of-Flight Aberration Correction and Spin Filtering of Electron Beams

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Time-dependent electron detection e.g. using a delayline detector paves the way towards a new way of aberration correction. In this approach Scherzer's Theorem is circumvented by means of time-dependent fields and detection [1, 2]. A possible approach is to "cut" the electron image into picosecond time slices and finally mount the aberration-corrected partial images to a total image. Using a special type of low-energy microscope, all three momentum components of an electron beam (k_x, k_y via lateral imaging, k_z via the time of flight) can be resolved simultaneously with unprecedented precision, leading to ***time-of-flight momentum microscopy***.

An additional imaging spin filter yields ***high contrast magnetic images*** or ***spinfiltered k-distributions*** and is suitable for the direct observation of magnetization structures on ferromagnetic surfaces and their ultrafast dynamics. Stern-Gerlach-type spin filters for electrons are impossible because of the interplay between Lorentz force and Heisenberg uncertainty relation [3]. All previous spin polarimeters are based on scattering on high-Z materials and are inherently single-channel methods characterized by low figures of merit of typically 10^{-4} to 10^{-3}. We use a novel imaging polarimeter based on spin dependent low-energy electron diffraction from W(100) or Ir(100) under specular reflection. A device built at the Max Planck Institute in Halle can resolve 3800 pixels and is characterized by a 2D figure of merit of 8 [4]. Alternatively, the imaging spin filter can be used behind the exit of a hemispherical energy analyzer [5].

In this contribution all aspects of time-of-flight aberration correction and spin-filtering will be discussed, with emphasis on the application for the diagnosis of electron beams.

Fruitful cooperation with C. Tusche, A. Krasyuk and J. Kirschner (MPI Halle) and M. Kolbe, D. Kutniakhov, P. Lushchyk and K. Medjanik (Univ. Mainz) is gratefully acknowledged. Projects are funded by DFG (Scho341/9) and Stiftung Rheinland Pfalz für Innovation (# 886).

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CsBr based photoelectron nano sources

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Abstract

Electron beam lithography writing tools have demonstrated capability of delineating features of less than 10 nm. However, the throughput capabilities for present and future device generations are limited for single beam writing tools. A multiple electron beam tool utilizing an array of 30 photoelectron sources of about 300nm diameter was demonstrated a few years ago. However, the reduction electron optics utilized to decrease the electron beam size to less than 50 nm required a multi-beam crossover point. Electron-electron interactions at the crossover point causes beam blurring limiting the tool resolution and placement accuracy for future device generations. This problem can be eliminated through the use of an array of nanometer size electron sources that may be independently focused with a uniform magnetic field, eliminating the crossover point in previous systems. The electron sources consist of C shaped apertures <40nm in a metal film utilizing plasmonic resonance to enhance the 257 nm laser light transmission. The metal apertures on a metal film deposited on a transparent substrate are coated with a CsBr film to enhance the photoelectron emission of the semitransparent metal substrate at 257nm. The mechanism for the observed photoemission enhancement below the CsBr band gap (~7.3 eV) and the application to reliable electron sources with low energy spread will be presented along with experimental results, including light transmission and electron emission performance of 20 nm C apertures fabricated with a Zeiss He microscope.

Low-energy (0-20 eV) Electron Beam for Chemical Control in Surface Modification

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Mechanical, electronical, and chemical properties of a substrate can be tuned by changing its surface composition. Electron-beam chemical lithography was applied successfully in the literature to self-assembled monolayers (SAMs) of thiols deposited on gold [1]. Generally, the focussed electron beam energy belongs to the keV range. At such high energy, the chemical specificity is low due to the large number of dissociating open channels, and the release of secondary low-energy electrons. By contrast, low-energy (0-20 eV) electrons (LEE) allow to induce, control, and orientate chemical reactivity, by initiating selective and efficient dissociative processes at sub-excitation energies [2].

Low-energy electron interactions and induced surface chemistry were studied in thiol SAMs deposited on gold. Selective modification of terminal functions in 11-Mercapto-undecanoic acid SAMs [3], and of aromatic spacers in terphenylthiol SAMs will be discussed.
LEE irradiations are performed using a commercial gun, which supplies, depending on electron energy, a current of 0.5-5.0 μA on a ~2-7 mm spot, with a resolution of about 500 meV. Exposures of typically 10-700 e^- per adsorbed molecule (uncertainty estimated to 50%) are used for processing. The electron induced primary processes are studied by electron induced desorption (ESD) of neutral fragments. The resulting chemical modifications of the substrates are probed by HREEL vibrational spectroscopy (High Resolution Electron Energy Loss Spectroscopy).

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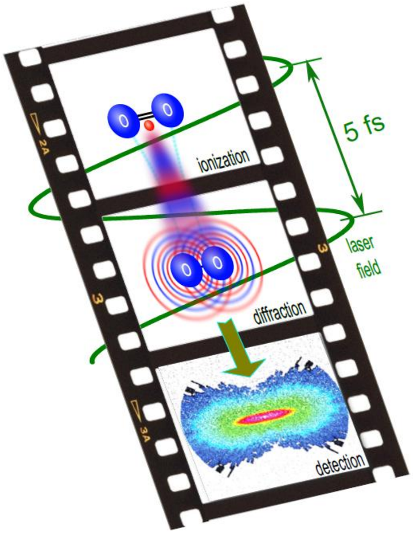
Talk: Ultrafast Molecular Imaging with Laser-Driven Electron Diffraction

Speaker: Cosmin Blaga, Ohio State University, Agostini-DiMauro Atomic and Molecular Research Group



Abstract

Filming a chemical reaction as it takes place in real-time requires a “camera” capable of delivering sub-Ångstrom and femtosecond spatio-temporal resolutions. One method of achieving such resolutions is based on laser-driven electron diffraction. First, a molecule placed in a strong mid-infrared field is tunnel ionized. Then, a laser cycle later, the field-accelerated photoelectron is driven back to diffract on its parent molecule. Finally, from measured high-resolution photoelectron angular distributions, diffraction images in the form of elastic differential cross sections reveal molecular structural information. In this talk, I will present the first experiment that directly imaged the relaxation of a molecule following tunnel ionization [1].

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Ring-cathode focused electron beam columns

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This paper describes the aberration characteristics of ring-cathode electron beam focused columns. Ring-cathodes are expected to have emission currents that are several orders of magnitude higher than their conventional single-tip counterparts, due to their larger area of emission. A wide-variety of different cold field emitter geometries can for instance be fabricated from Carbon Nanotubes (CNTs) [1], and it should be possible to fabricate nano-size CNT ring-cathode cold field emitters, ones that have radii in the tens to hundreds micron range and edge thicknesses that are less 100 nm. On the other hand, new techniques of electron beam focusing are required in order to form a nano-meter size electron probe from a ring-cathode. Direct ray tracing simulation results in this paper show how electron beam focused columns can be designed to use ring-cathodes. There are certain situations where the chromatic and geometric aberrations of lenses in such columns can be made to cancel, greatly minimizing the spot diameter of the electron probe. Simulation results predict that it should in principle be possible to focus microamperes of electron beam current into nanometer probe diameters with such techniques.

On possible ring-cathode electron focused beam column design is illustrated in Figs. 1a-c. Electrons leave the emission plane from off-axis points, are accelerated through a common anode, and form a virtual source spot as they exit the gun unit with relatively small angles. A weak electric lens in the gun unit helps to reduce their angular spread. It turns out that for points either on or close to a certain emission radius, off-axis geometrical aberrations generated within the gun unit cancel out with corresponding aberrations generated in the objective lens, greatly reducing the final probe size, this is illustrated by the simulation results shown in Figs 1d and 1e. For the example gun/lens column shown in Fig. 1, nano-emitters having a radius of 152 μm with emission angles ranging from -100 to 100 mrad are predicted to generate a RMS probe radius of 10 nm. Although only one focusing lens is required beyond the gun unit, it is useful to add an intermediate point of focus at which an aperture can filter the angular spread, as shown in Figs 1b and 1c. This design minimises linear geometric aberration variations, other designs that correct for both higher-order geometrical aberration terms and chromatic aberration will be described.

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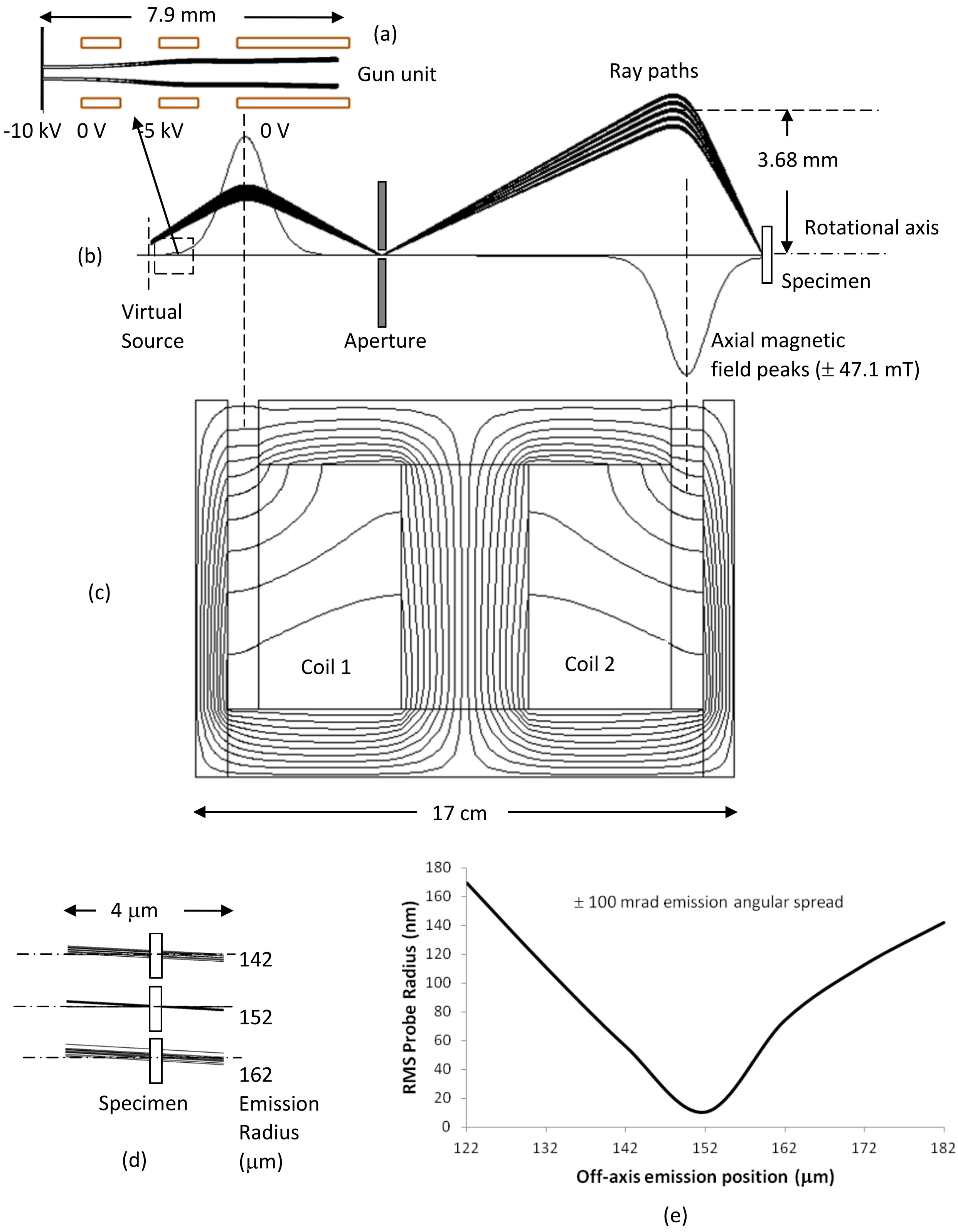
7.9 mm
(a)
Gun unit
-10 kV
0 V
5 kV
0 V
Ray paths
3.68 mm
Rotational axis
(b)
Specimen
Virtual
Source
Aperture
Axial magnetic
field peaks (± 47.1 mT)
(c)
Coil 1
Coil 2
17 cm
4 μm
142
152
162
Specimen
Emission
Radius
(μm)
(d)
± 100 mrad emission angular spread
RMS Probe Radius (nm)
180
160
140
120
100
80
60
40
20
0
122
132
142
152
162
172
182
Off-axis emission position (μm)
(e)

Ion emission from a dipole blocked cold atomic gas

Kevin Weatherill

Duhram University

We present progress towards a source of single ions based upon the process of Rydberg blockade. When the volume of the excitation region is smaller than the 'blockade radius', only a single atom can be excited at a time. The single atom can then be ionized and a single ion produced.

We also present results from a frequency stabilized 3-color laser system which provides narrow band excitation to high lying Rydberg states [1,2]. The system is based upon inexpensive, compact and simple to use diode lasers.

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NOVEL ION TRAPS FOR DETERMINISTIC ION Implantation

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Novel ion trap geometries for deterministic high resolution ion implantation are presented which are obtained by highly efficient field calculation methods [1]. I will present our recent progress with a segmented ion trap with mK laser cooled ions which serves as a high resolution deterministic single ion source. It can operate with a huge range of sympathetically cooled ion species, isotopes or ionic molecules. We have deterministically extracted a predetermined number of ions on demand [2] a first step in the realization of an atomic nano assembler, a novel device capable of placing an exactly defined number of atoms or molecules into solid state substrates with sub nano meter precision in depth and lateral position. Current state of the art production techniques do not offer these possibilities and pose a major production problem for the realization of scaled solid state quantum devices. The project is motivated by the quest for novel tailored solid state quantum materials generated by deterministic high resolution ion implantation. The major goals are the deterministic generation of colour centers or quantum dots, placing them in special geometries in order to exploit the mutual coupling for the realization of macroscopic functional systems and interfacing them to the macroscopic world with the help of electrode structures, single electron transistors and optical micro cavities. Targeted applications range from quantum repeater, correlated triggered multi photon sources, calibrated single photon sources, quantum computation circuits and sensors with unprecedented sensitivity. Driven by the quest for novel trap geometries for precision ion implantation I will also present new planar and three dimensional trap geometries which allow for the application of variable rf fields for precise positioning of ions in two dimensions [3] targetting parallel extraction of ions from a chip trap.

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Bypassing Liouville: Deterministic single-ion-implanted devices for reading atom quantum states

David Jamieson

Liouville'sTheorem, that phase space is conserved, links our ion sources to our potential applications in microscopy and nanofabrication. Cold beams confined to a very small phase space offer the potential, via Liouville, of transport onto the sample for high resolution applications. However, not all useful beams can be sourced from a small phase space. We are developing a precision single-ion deterministic doping system based on the collimation of a plasma ion source by a scanned nanostencil coupled to on-chip ion impact detector electrodes. We seek to address the challenge of the International semiconductor roadmap for 2011 which identified the need for deterministic doping to fabricate next-generation of silicon nano-scale complementary metal-oxide-semiconductor field effect transistors and other devices. The channel lengths of present generation devices are now so small (~20 nm) that it is comparable in size to the Bohr orbit of the donor electrons (~1.22 nm for Si:P)and the device performance is strongly influenced by statistical variations in donor concentration and the location of single donors. As well, when devices are cooled to milli-Kelvin temperatures, selected devices are sensitive to the internal quantum mechanical degrees of freedom of single dopant atoms.A specific goal of our work is to exploit these quantum phenomena in the development of a solid state silicon quantum computer which encodes information in the quantum states of a P donor atom electron and nuclear spins. We have succeeded in building a device allowing us to program and read-out both the electron and nuclear spins of a single engineered P atom. These spins are quantum bits which are the key components of the quantum internet of the mid-21st C.

A laser-cooled Si atom source for Kane quantum computers

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In 1998, Bruce Kane proposed a solid state quantum computer architecture that has the potential to be scalable to kilo-qubits or even mega-qubits.[1] It utilizes an array of single ^{31}P dopant atoms embedded in a ^{28}Si lattice. The challenge for this concept is the placement of one and only one ^{31}P atom at each site, ~10 nm below the surface and separated ~20 nm, with about 1 nm precision in the Si substrate. To avoid ion straggling, the P ions should be deposited at low energy, ~100 eV. Even the best commercial ion guns do not have sufficiently small phase space to accomplish this task. Deposition of one and only one ion in a site is also problematic.

A laser cooled and trapped single atom in a magneto optic trap, followed by resonant photo-ionization, provides a deterministic ion source with a small enough phase space to achieve the required precision in deposition [2]. Current laser technology does not allow for the direct cooling and trapping of P atoms, as the transition at 177 nm is in the vacuum ultraviolet region. However, the $3s^2 3p^2\, {}^3\mathrm{P}_2 \rightarrow 3s3p^3\, {}^3\mathrm{D}^o{}_3$ transition in silicon at 221.7 nm is a cycling transition that may be used for the laser cooling and trapping of silicon atoms. In particular, the radioactive isotope ^{31}Si would beta decay after deposition into ^{31}P. Such a deterministic single ion source of ^{31}Si could provide the desired ^{31}P qubits for a Kane quantum computer.

We will report on the status of our experiment. We have verified spectroscopically favorable conditions for trapping of all four isotopes of Si and for efficient resonance ionization.[3] The magneto-optic trapping of Si atoms is underway. The ion optics for extraction of single Si^+ ions and low energy implantation into a Si substrate are being designed.

This work is supported by the W. M. Keck Foundation.

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Single ion implantation for nanoelectronics and the application to biological system

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1. History of single ion implantation(ref.1)

Ion microprobe system(IMP) is a modified version of Rutherfordbackscattering system(RBS) with a function of both depth and areal resolution and useful for three dimensional element analysis. Increasing ion current for better statistics, however, had a disadvantage of serious damage in a target, so we decided to extremely reduce the ion current and finally to single out each ion from the ion beam.The single ion microprobe(SIMP) developed in this way was used for the first time to study site dependence of radiation hardness in semiconductor devices such asMOSFETs, pn junctions and Schottky diodes.

In the middle 1990s, size reduction of semiconductor devices went beyond the reach of the SIMP because of the insufficient areal resolution. In the course of our study to seek for much better areal resolution of the single ion technology, we found that, in the era of nm size devices, the distance between dopant atoms became comparable to the device size, and that the fluctuation in device functions due to fluctuation in dopant number could not be negligible. Finally in 1994 we developed a single ion implantation (SII) as a tool to suppress device function fluctuation induced by fluctuation in discrete dopant number. The first SI implanter was born in 1996 by adding some new features to an existing focused ion beam (FIB) system. The new features were extraction of single ions, a singularity of extracted ions, detection of single ion incidence and high aiming precision. By improving these technological factors step by step, we have finally realized the controllability of number and position of dopant ions.

2. Novel applications of SII

A Single atom devices(ref.2, ref.3, ref4)

We fabricated silicon transistors containing two, four and six arsenic ions implanted in one dimensional array along the channel using SII method. The quantum transport was measured through the D^0 and D^- states of the arsenic ions at low temperature in the subthreshold region. Two different transport mechanisms contributedto the deterministically doped device: the Coulomb blockade and the Hubbard bandformation. In case of the two arsenic donorsample, the Coulomb blockade was dominant, andeach current peak was isolated. In case of the six arsenicdonor sample, the Hubbard bandformed, and the current peaks overlapped. These results indicate that our deterministic single-ion doping method is more effective and reliable for single-atomdevice development and pave the way towards single atom electronics for extended CMOS applications.

B　SII to livingcells(ref.5)

We performed gold atom doping into live cells by using the FIB implantation method. We evaluated the viability of the gold-implanted cells by measuring the concentration of adenosine triphosphate (ATP), which is an intracellular energy source produced in the mitochondrial membrane. The viability of the implanted cells was found to be 20% higher than that of the unimplanted control cells. The implanted atoms might promote the energy generating processes within the mitochondrion. These results suggest that the viability of live cells can be modulated by accurately controlling the dopant atom numbers. Our ion implantation technique may be considered as a more accurate tool to quantitatively elucidate the dose-dependent effects of dopants than the conventional methods.

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