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Viruses are continuously changing as a result of genomic structural variations, including mutations and recombination through exchange of genetic information. These genomic variations can result in pathogenicity. These altered viruses may be able to cause disease in previously resistant or immune hosts. Early detection of these genetic variations is hence of paramount importance in early detection of new viral strains and subsequent development of anti-viral prophylaxis and vaccines. The golden standard for selection and amplification of relevant genomic regions is RT-PCR, which is relatively time and labour expensive and restrictive in the range of targeted structural variation. Each genetic variation requires a different primer.

We propose a detection device based on nanofluidic confinement for rapid screening of unlimited genomic variations of viral pathogens with extremely high selectivity and sensitivity which precludes RT-PCR. To investigate larger scale genetic variations we propose to isolate the complete genome and to linearize it on an array of channels, each with a cross-section of about 100 nm. Fluorescence beacons are used to map out the genetic sequence and to trace structural variations such as inversions, translocations, repeats, and duplications along the complete genome in a single scan.

Various fabrication protocols of polymeric nanofluidic lab on chip (LOC) devices are discussed in this paper. Proton beam writing and nanoimprinting are combined in fabricating nanosized sealed PMMA and X-PDMS channels for DNA linearization and characterization purposes. Employing an optimized nanoimprinting and thermal bonding protocol, fabrication of PMMA nanofluidic LOC devices can be completed in a short time, by non-experts in the field. The working principle of monitoring of large scale genomic structural information will be discussed through mapping of individual DNA molecules. The authors would like to acknowledge the support from the US Air Force (Grant No. FA9550-20-1-0249).
Secondary Ion Mass Spectrometry (SIMS) is an extremely powerful technique for analyzing surfaces, owing in particular to its ability to detect all elements from H to U and to differentiate between isotopes, its excellent sensitivity and its high dynamic range. SIMS analyses can be performed in different analysis modes: acquisition of mass spectra, depth profiling, 2D and 3D imaging. Adding SIMS capability to FIB instruments offers a number of interesting possibilities, including highly sensitive analytics, in-situ process control during patterning and milling, highest resolution SIMS imaging (~10 nm), and direct correlation of SIMS data with data obtained with other analytical or imaging techniques on the same instrument, such as high resolution SE images or EDS spectra [1,2].

Past attempts of performing SIMS on FIB instruments were rather unsuccessful due to unattractive detection limits, which were due to (i) low ionization yields of sputtered particles, (ii) extraction optics with limited collection efficiency of secondary ions and (iii) mass spectrometers having low duty cycles and/or low transmission. In order to overcome these limitations, we have investigated the use of different primary ion species and of reactive gas flooding during FIB-SIMS and we have developed compact high-performance magnetic sector mass spectrometers operating in the DC mode with dedicated high-efficiency extraction optics. We installed such SIMS systems on different FIB based instruments, including the Helium Ion Microscope [3-5], a FIB-SEM DualBeam instrument and the npSCOPE instrument, which is an integrated Gas Field Ion Source enabled instrument combining SE, SIMS and STIM imaging with capabilities to analyse the sample under cryo-conditions [6]. Here, we will review the performance of the different instruments with a focus on new developments such as cryo-capabilities and new detectors allowing parallel detection of all masses, showcase methodologies for high-resolution 3D chemical imaging, present a number of examples from various fields of applications (nanoparticles, battery materials, photovoltaics, micro-electronics, tissue and sub-cellular imaging in biology, geology,...) and give an outlook on new trends and prospects.


This project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under grant agreement No. 720964.
1068-Ion irradiation of liquid targets under vacuum using the capillary microbeam technique

Hidetsugu Tsuchida 1

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Technical development of ion irradiation of liquids is becoming increasingly important for expanding the applications of ion beam materials analysis. Recently, we have developed a new method for irradiation of liquid microjet targets with fast ions using the capillary-microbeam technique. This method minimizes the contribution of radiation to the gas phase region formed around the liquid jet. Figure 1 shows a photograph of a liquid jet target being irradiated with an ion beam produced by the capillary-microbeam method. This apparatus can perform time-of-flight mass spectrometry for secondary ions emitted from the liquid surface by irradiation.

In this talk, we will discuss two topics. The first is the transmission properties of fast heavy ions including cluster ions through a tapered glass capillary [1,2]. We show that the transmission properties depend on the velocity of ions. The second is the ion irradiation of liquid microjet targets using the capillary-microbeam technique. As an example of research using this method, I will also talk about basic research on radiation damage to biomolecules in water


Contributed talks

1014-Ion beam based micro fabrication of graphite patterned diamond sensors for in vitro detection of excitable cells activity

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Action potentials (APs) generation and synaptic quantal release of neurotransmitters play a fundamental role in the cellular mechanisms underlying brain functions, being at the basis of information transmission and signal communication in neuronal microcircuits. Their proper detection is therefore essential to understand neuronal signalling during brain activity.

In the present work we report on the microfabrication and characterization of diamond-based multifunctional micro-patterned graphitic multielectrode arrays able to resolve APs waveforms and neurotransmitter release [1-2]. The sensors were constructed through a three-dimensional patterning process of single-crystal diamond substrates by means of MeV ion-beam-based lithography, allowing the direct fabrication of graphitic micro-channels embedded in the electrically insulating diamond matrix.
Due to the typical damage profile of high-energy (MeV) ions, highly ion-damaged diamond layers were fabricated below the crystal surface and converted to graphite after a high temperature thermal annealing. Being electrically conductive, the micro-channels allows to investigate the cellular activity both in terms of neurotransmitter secretion (quantal exocytic events) and electrical signal generation (action potential firing). Proof-of-concept in vitro experiments on cultured neurons and cardiac tissue were performed [3]. Quantal secretory events were amperometrically recorded from in-vitro mouse dopaminergic neurons, while potentiometric measurements of AP generation were recorded from both hippocampal neuronal networks and intact sinoatrial nodes. These results confirm the key role played by ion beam micro-lithography in the fabrication of a diamond-based biosensor for the multi-parametric detection of chemical and electrical signals, while in the context of neuroscience research they represent a fundamental step for the simultaneous in vitro measurement of the two types of signals from the same biological sample.


1016-IBIC analysis of a 2D diamond position sensitive detector fabricated by ion beam deep lithography

Jacopo Forneris 1, Georgios Provatas 2, Federico Picollo 1, Sviatoslav Ditalia Tchernij 1, Marko Brajkovic 2, Andreo A. Crnjac 2, Valentino Rigato 3, Milko Jaksic 2, Ettore Vittone 1

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In multi-electrode devices charge pulses at all the electrodes are induced concurrently by the motion of the excess charge carriers generated by a single MeV ion. This charge- sharing effect is such that the pulse amplitude at each sensitive electrode depends on the device geometry, its overall electrostatic configuration and the charge transport properties of the detector material. Therefore, therefore, the analysis of the charge pulses induced in each electrode, can provide information on the position of impact of individual ions. In previous works [1,2], this principle has been explored to demonstrate the effectiveness of the charge sharing approach to detect the location of the impact in a one-dimensional geometry. In this work, we investigate the 2-dimensional position sensitivity of a diamond detector fabricated by deep ion beam lithography. Three independent, ~30 µm spaced sensitive electrodes were fabricated with micrometric resolution in a high-purity single-crystal diamond sample upon irradiation using a 4 MeV C\textsuperscript{3+} ion beam. The device was then exposed to a 2 MeV Li\textsuperscript{+} ion micro-beam to acquire charge collection efficiency (CCE) maps by means of the Ion Beam Induced Charge (IBIC) technique. The IBIC signal was acquired by all the sensing electrodes, and the corresponding maps were cross-analysed in order to assess the spatial dependence of the CCE on the nominal micro-beam scanning position. A correlation between the maps acquired from the three electrodes was established on the basis of the Shockley-Ramo-
Gunn theory and the charge conservation principle. Such analysis revealed a 2-dimensional position sensitivity of the device with micrometric resolution at the center of the active region, corresponding to the portion of the device where charge sharing between all the three electrodes was observed.


1036-High resolution mapping of defect centres in single ion detectors for quantum computing applications

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Background: The long-lived electronic and nuclear coherent spin states of single 31P donors implanted ~20 nm deep in a 28Si “spin vacuum” [1] are a promising platform for universal quantum computing [2]. Moreover, the recent emergence of the flip-flop qubit architecture [3] relaxes the demands on the donor placement precision to 10~15 nm. Implantation of 31P-ions at <14 keV energy meets these constraints and thus presents a promising industry-compatible method of donor-qubit establishment.

Materials and methods: The design of the quantum device also allows it to double as a single ion detector, whereby electron-hole (e-h) pairs created by each ion strike are separated by an internal electric field and detected via the Ion Beam Induced Charge (IBIC) technique [4]. However, the required low implantation energies generate only 500~1500 e-h pairs per ion strike. To preserve a high single ion detection confidence, trapping and recombination of e-h-pairs at defects in the silicon bulk as well as the surface oxide interface must be minimised. A thorough device evaluation procedure is therefore key to the development and fabrication of single ion detectors.

Results: We characterise the charge collection efficiency (CCE) of our latest detector generation connected to an ultra-low noise pre-amplifier circuit and exposed to a scanned 1 MeV He+ ion beam of ~250 nm spot size. We focus particularly on the influence of gate oxide quality, and wire bond strain effects. The obtained high-resolution IBIC CCE maps are used to assess and optimise our detector fabrication protocol for reliable donor-qubit array engineering. We also apply our low-noise electronics for use in high-resolution Rutherford backscattering spectroscopy [5].

Conclusions: The use of a scanned, focused nuclear microprobe and an ultra-low noise preamplifier are valuable tools for characterising the suitability of customised single ion detectors for use in quantum computing applications.
1037-Controlled single ion implantation through micro nano apertures for donor qubit devices in silicon

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The unique attributes of group-V-donors implanted in a 28Si host matrix make them attractive qubits for large-scale devices1,2,3. However, the up-scaled manufacture of such architectures requires significant advances in present semiconductor device fabrication techniques. In previous studies, we have demonstrated that the charge induced by a single ion, stopping in the silicon substrate, provides a detectable signal employable for the controlled implantation4. These signals are part of a deterministic implantation strategy for the fabrication of ordered dopant arrays. We present further advances in the detector development and charge sensitive electronics that provide access to signals induced by low-energy ions (7-35 keV), which are required for a shallow donor placement (<25 nm) and reliable donor-qubit control. Our detection approach is demonstrated in combination with an integrated ion-aperture scanner to address the critical issue of precise spatial ion direction for controlled array formation. With the combined system, 14 keV P+ ions are detected with a confidence approaching 99.9% at near-room temperature operation and therefore sufficient for fabricating scalable donor-qubit arrays. Further insights into the ion-solid interaction are extracted from numerical Crystal-TRIM simulations and discussed within the context of ion-induced signals and related dopant placement characteristics. Here, we describe an enhancement of ion implantation - an industry-standard top-down doping tool - for implanting single donor atoms compatible with the constraints of silicon quantum device fabrication.

1040-Micro free standing 3D structures processed by focused hydrogen ion beam (FHIB)

**Hidetaka Hayashi**, Yuki Nohara ¹, Hiroyuki Nishikawa ²

_EcoDesign Promotion Network Head office Shisui-machi-Japan_ ¹  _Shibaura Institute of Technology Electric Tokyo-Japan_ ²

We have reported that FHIB (Focused Hydrogen Ion Beam) is useful to make multiple depth structure on PET. This structure is intending to fabricate surface electronic component in high frequency (GHz to THz) band (1). In this report we propose another possibility of FHIB to make micro free standing 3D structure. A free standing structure is a part of a skeleton circuit structure (2) that is made by eliminating surrounding material of a circuit except terminal posts. The circuit could have freedom of movement and full surface interfacing with surrounding environment such as electronic, optical, mechanical and chemical energies or signals. The structures were formed on thin plastic surface layer by focused H3⁺ and proton (H⁺) beams. As the depth of penetration of proton is precisely controlled by acceleration voltage and the pattern is directly drawn by FHIB which is less than a few microns in size we can make micron scale 3D structures in very thin (20 micrometers or less) plastic layers. We can use this technology to modify thin plastic layer by making micron scale 3D structures to add mechanical, optical and electronic functionality. The strong penetration capability on composite plastics is also useful to add various functionalities on surface protective layers of many components.

Posters

1007-Fabrication of micro components for X ray optics using proton beam writing technique

**Aleksandr Ponomarev** ², Vladimir Rebrov ¹, Sergey Kolinko ¹, Vadim Salivon ¹, Hleb Polozhii ¹

_Institute of applied physics NASU Physics of charged particle beams Sumy-Ukraine_ ¹

Using in an interferometric X-ray phase-contrast imaging method of objects visualization based on 3-phase diffraction gratings with certain physical and geometric parameters, it is possible to receive phase-contrast images of the object under study with an ordinary X-ray tube as a source of radiation. This avoids the use of synchrotron coherent radiation. Typically, these gratings are made using LIGA technology which is a projection technology using high-cost masks. An alternative technology is the proton-beam writing technique, which provides direct exposure resistive material by means of the focused proton beam from electrostatic accelerator with energy of several MeV. Proton beam writing is a direct writing technique which gives possibility to fabricate 3D micro- and nano-dimensional structures in resistive materials. The structures have high aspect ratio with vertical, smooth side walls and low line-edge roughness. This presentation describes the process of proton beam formation focused into a thin line using a separated triplet of magnetic quadrupole lenses. This significantly reduces the exposure time of the resistive material during fabrication of diffraction gratings. Images of diffraction gratings and their geometrical dimensions are given.
1015-An ion beam spot size monitor based on a nano machined Si photodiode probed by means of the Ion beam Induced Charge technique
Jacopo Forneris 1, Georgios Provatas 2, Marko Brajkovic 2, Andreo Crnj 2, Sviatoslav Ditalia Tchernij 1, Valentino Rigato 3, Milko Jaksic 2, Ettore Vittone 1

University of Torino and INFN Torino Physics Department Torino-Italy 1 Institut Ruder Boskovic Laboratory for Ion Beam Interactions Zagreb-Croatia 2 INFN National Laboratories of Legnaro Legnaro-Italy 3

In this work the utilization of the Ion Beam Induced Charge technique is explored to assess the resolution a 2 MeV Li+ ion micro-beam raster scanning micrometer-sized FIB-machined hollows in a silicon photodiode. The resolution of the ion beam was assessed by measuring the drop in the charge collection efficiency across the edges of the hollows’ sidewalls. The method was preliminarily assessed to measure the spot size of a laser beam by means of confocal microscopy and photocurrent mapping, and was subsequently exploited to estimate the resolution of a focused ion beam in comparison with the achieved by means of a standard scanning transmission ion microscopy (STIM) experiment.

The experiments performed suggest the viability of the proposed method to define an upper limit of the beam resolution, whose accuracy depends upon the operating bias voltage, the size of the hollows and the electronic properties of the material. In principle, this approach could offer an effective method for the evaluation of the resolution of a micro-beam even in rarefied currents regimes for automated processes (micro- and nano-lithography, ion implantation at the nanoscales) in which the utilization of the STIM technique, requiring a separate target and a dedicated detection setup, might not be compatible with the required high throughput with high positional accuracy.
1018-Angle Resolved Differential IBIC analysis of silicon power diodes.
Michele Pezzarossa 1, Enrico Cepparrone 2, Milko Jaksic 3, Georgios Provatas 3, Donny Domagoj Cosic 3, Milan Vičentijević 3, Ettore Vittone 2

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This contribution describes both an experimental methodology based on the Ion Beam Induced Charge (IBIC) technique and the relevant interpretative model, which were adopted to characterize the electronic features of semiconductor diodes.

The experiment was carried out at the Ruder Boskovic Institute of Zagreb (HR) within the UE-RADIATE project, using rarefied focused proton beams to induce charge signals on commercial p-i-n silicon diodes. A thousand of IBIC spectra were acquired by irradiating a region of about (0.1x0.1) mm$^2$ of the diode frontal electrode under different experimental conditions, which include the energy of protons ranging from 1.2 to 2.0 MeV, the angle of incidence of the ion beam ranging from -50° to +50° with respect to the normal of the sample surface, and the applied reverse bias voltages.

The modulation of the ion probe range obtained both by using different proton energies and/or by tilting the sample, allowed the charge collection efficiency scale to be accurately calibrated, as well as the dead layer beneath the thick (6 micrometer) Al frontal electrode to be measured with a sub-micrometer resolution.

This calibration was essential to measure the carriers’ lifetime through the analysis of IBIC spectra resulting from charge signals generated by different ionization profiles of the ion probes, combined with different extensions of the depletion layer, determined by the application of reverse bias voltages, to realize fully and partially depletion conditions.

The analysis was carried out adopting an analytical model extracted from the basic IBIC theory; although the many simplified assumptions adopted, the model proved to be suitable to interpret the behavior of the IBIC spectra as a function of all the experimental conditions (ion energy, tilting angle, applied bias voltage) and to provide a measurement of the carriers lifetime in the intrinsic region.
1070-Harnessing the angular diversity of a large array for PIXE imaging Maia detector powered Nuclear Microscopy

Chris Ryan ², Jamie Laird ², Robin Kirkham ¹, Siyu Hu ¹, Antony van der Ent ³, Murray Jensen ¹, Gareth Moorhead ¹

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The Maia detector array not only provides a large collection solid-angle and 384 independent detector channels, which enables very high count rates at low pileup and dead-time (Kirkham et al., 2010; Ryan et al., 2014a), the wide range of take-off angles provides sensitivity to sample structure, sampled by lateral absorption contrasts, or surface topology. For a single detector, these effects lead to misleading artefacts, such as edge enhancement or shadowing. However, the multiple perspectives afforded by a large array can be used to eliminate these artefacts or to probe the structural contrasts that lead to them.

To begin, this talk will outline the Maia detector technology and show some examples of Maia powered PIXE imaging of biological and geological samples, which exhibit count rates up to ~8 M/s and enable a spectral dynamic range of 4 orders of magnitude between major and trace elements to be captured (Laird et al., 2019a,b). Then it will shift to using the angular diversity of the Maia array, by selecting detectors in groups of related take-off angles, (i) to probe the depth of features in a sample (adapting the method of Ryan et al., 2014b), (ii) to image dipping structures reflecting contrasts in composition and absorption, and (iii) to enhance the 3D perception of sample topology and structure.


Ryan, C.G., Siddons, D.P., Kirkham, R., Li, Z.Y., de Jonge, M.D., Paterson, D.J., Kuczewski, A., Howard, D.L.,


1058-High energy ion microbeam and its interdisciplinary applications

**Guanghua Du** 1, Jinlong Guo 1, Wenjing Liu 1, Ruqun Wu 1, Jing Zhao 1, Guangbo Mao 1, Cheng Shen 1, Hongjin Mou 1, Yaning Li 1

**Institute of Modern Physics Materials Research Center Lanzhou-China** 1

When heavy ion beam with energy from MeV to GeV is incident on the target material, the target material distributed along the ion trajectory will be excited or ionized, which will cause lattice damage, polymer chain break or cross-linking in the material and then result in nanoscale latent track, cluster damage and single event effect. The high energy microbeam facility of Lanzhou National Laboratory of Heavy Ion Accelerator is the highest energy microbeam system in the world which uses triplet-quadrupole magnets to produce micron sized high energy ion beams of up to several GeVs. This talk first introduces the advantage of high energy ion beam in the interdisciplinary application of microbeam facility, including nanostructure fabrication using single ion track, single event effect studies and single ion localization microscopy.
1021-The MACHINA Project: A novel design for transportable IBA measurements

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MACHINA (Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis) is a joint project of the Italian National Institute of Nuclear Physics (INFN), through its network for the study of Cultural Heritage INFN-CHNet, and the European Organization for Nuclear Research (CERN). The purpose of this project is the construction of a compact, transportable accelerator system, fully dedicated to in situ Ion Beam Analysis (IBA) of materials of interest in the Cultural Heritage field. Both institutions have contributed to the project with their experience in development, use and application of particle accelerators. CERN in particular has developed the accelerating cavities (HF-RFQ) and has carried on the study of beam dynamics, INFN-CHNet is responsible for the ion source, diagnostic devices, detectors, control/acquisition system and for the use of the system on works of art. MACHINA will be normally based at the laboratories of the Opificio delle Pietre Dure (OPD) in Florence, but it will also be possible to move it for short periods to other laboratories and museums, thus avoiding the always risky and sometimes impossible transportation of works of art (see for example the case of frescoes).

The presentation is organised as follows: a brief introduction of the project, the main points on which MACHINA is based, its main pros and cons, the current status of the project and performed tests, ongoing works.

1013-A high solid angle detector system for Rutherford Back Scattering measurements

Robert Frost¹, Per Kristiansson ¹, Mikeal Elfman ¹, Jan Pallon ¹

Lund University Physics Lund-Sweden ¹

The use of a DSSSD (Double Sided Silicon-Strip Detector) in IBA applications [1] allows for experiments with high multiplicities due to the detectors granularity, reduced beam-time due to high solid-angle and, simultaneously, provides specific angular information about the particles detected. Previous work has shown the effectiveness of this tool in NRA (Nuclear Reaction Analysis) [2, 3, 4] and ERD (Elastic Recoil Detection) [5, 6, 7] techniques, demonstrating the detectors high rate, virtually pileup free operation and the possibility of detailed measurement of angular distributions. In the present work a DSSSD is used for RBS (Rutherford Back-Scattering) analysis. Details of the experimental setup are presented, which includes a pre-sample charge measurement system [8] to record beam-current free from sample dependent effects.
and a large area SDD (Silicon Drift Detector) for simultaneous PIXE analysis. Preliminary results from the analysis of test samples are discussed and are contrasted with simulation to demonstrate proof of principle. It is shown that, with this setup, it is possible to perform RBS measurements in solid angles of >3 sr.


Contributed talks

1045-Some recent developments in nuclear microprobe instrumentation

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Frank Watt  
Oxford Microbeams Ltd and  
Centre for Ion Beam Applications, Dept of Physics, National University of Singapore

The last few years have seen developments in instrumentation by Oxford Microbeams Ltd and CIBA. These developments will be briefly discussed, and include:

a) A remote controlled motorised slit system for use in radiation environments, based on the OM10 beam defining apertures. In most cases the motors can be fitted retrospectively to existing OM10 systems.  
b) Short magnetic scan coils for post-lens beam scanning. These are based on the OM25 ferrite cored box deflector coils, and were developed for external beam applications such as cell radiobiology, where a high integrity of beam location in the image plane is required for precise individual cell irradiations.  
c) Radiobiology irradiation system for multiple cell irradiation (millions of cells).

d) Many groups worry about potential lens misalignments, and the resulting deterioration of beam spot size. Although in a stable environment re-alignment is usually not necessary, there are situations (eg moving the beam line to a new location) where a realignment is necessary. We have produced a video which shows how to re-align the lenses to achieve optimum beam spot sizes.
1047-Advanced single and multi sensor SDD for PIXE applications

Del Redfern 1, Geoff Grime 2, Vladimir Palitsin 3

Hitachi High Tech Science America Inc Sales Chatsworth -United States 1 Oxford Microbeams Ltd. Oxford-United Kingdom 2 Ion Beam Centre, University of Surrey Guilford-United Kingdom 3

Hitachi High-Tech Science America, Inc. (HHS-US) is a manufacturer of Silicon Drift Detectors (SDDs) for various applications. We are very well known in the XRF and synchrotron community as the supplier of single-sensor SDDs as well as of the 4-sensor SDD, the Vortex® ME-4. Many different versions and models of single- and multi-sensor SDDs were produced for ultra-high-count rate applications.

This paper will discuss the characteristics required of a Silicon Drift Detector, including rise time, resolution, throughput, and sensor thickness and provide data to show the performance and characteristics of the Vortex SDD sensors.

The Silicon Drift Detector has become the standard for XRF type applications, but the main issue has always been the sensor thickness. The Vortex SDD became the only SDD available with a sensor thicker than 0.5 mm (500 µm) with the 1.0 mm thick sensor was introduced 4 years ago. Last year a 2.0 mm thick SDD sensor was introduced into the range of Vortex SDD. Data will be shown illustrating the performance of the different thickness sensors over a range of kV.

The designs of the different Vortex SDDs will be discussed including single and multi-sensor configurations.

Posters

1020-Nuclear nanoprobe virtual machine

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Nuclear microprobe/nanoprobe technology does shape MeV ion beams into beam spots of micrometer or nanometer dimensions, it is a powerful tool in a broad range of applications [1-4]. Many factors influence the beam focussing process, therefore it is desirable to have a simulation code package that allows an inexperienced operator to optimize simulated experimental parameters and to achieve simulated minimum spot sizes, which can then be compared with ‘real world’ results. In this work we present the Nuclear Nanoprobe Virtual Machine (NNVM), capable of simulating operational modes for both ‘Oxford triplet’ and ‘Russian quadruplet’ nuclear nanoprobe configurations based on MATLAB. NNVM allows to simulate the beam image on a quartz target and scans over grid structures. In NNVM, the user can define ion beam parameters (ion energy, ion type, beam diameter, beam divergence and brightness), layout of beamline, opening
of object slits and collimator, excitation currents of focusing lenses, grid structure and scan size. NNVM includes simulation of the effects of random variation on magnetic field of the focusing lenses and thermal expansion of the focusing lenses, both are well known to influence repeatability of a real nuclear nanoprobe.


1041-Spatial and temporal distribution of 1 MeV proton microbeam guided through an insulating macrocapillary

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When an incident ion beam enters an insulating capillary, whose axis is sufficiently tilted relative to the beam axis, incident ions will hit the inner surface of the capillary, and start to deposit electric charge, creating a charge patch. The electric field of this patch interacts with subsequently arriving ions, and deflects them towards the capillary exit before hitting the wall. The accumulated charges also interact with themselves, resulting in the charge-up of the inner wall in a self-organized manner. If the electric field due to the accumulated charges is strong enough to avoid the close collisions between projectiles and atoms of the capillary, the incident beam transmits the capillary in initial energy and charge state. The phenomenon is called ion guiding, and is important in several practical applications in ion beam technology.

The ion guiding effect was investigated by Monte-Carlo and molecular dynamics simulation methods. The incident beam was 1 MeV proton microbeam, the incident angle was 1°. The target was a single, macro-sized, straight, cylindrical shape poly(tetrafluoroethylene) capillary. Input data were generated by the widely used software packages, SRIM and WinTRAX. The equation of motion of projectiles, and the equation of charge redistribution are solved numerically. Atomic scattering and energy loss of projectiles upon collisions with the inner wall are taken into account. We found that at different phases of the beam transmission, different atomic processes result in the dynamic change of the beam shape. At the beginning, small angle multiple forward scatterings dominate the transmission, resulting an outgoing beam into a wide angular range and in a wide energy-window. Later, a guided fraction of the beam appears in a small, well-separated beam spot,
with kinetic energy equals to that of the incident beam. Finally, a stabilized, guided transmission forms, where the dominant fraction of the beam transmits the capillary with ion guiding, it is concentrated into a small beam spot, and a quadrupole-like focusing effect is identified [1].


1052-OMDAQ 3 the latest developments in the Oxford Microbeams data collection and processing software

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OMDAQ is now into its third decade as the software package underpinning the MeV ion microprobe systems manufactured by Oxford Microbeams Ltd. During this time it has been under continuous development and this presentation summarises the capabilities of the latest release.

Detector hardware options: Interfaces to a wide range of detector signal processing hardware including digital signal processors by Caen, Rayspec and Brightspec, Time to digital converters by Kore (for TOF applications) and direct parallel inputs from NIM ADCs such as FastcomTech or Canberra.

Beam scanning options: As well as the standard point, line and 2-D raster scanning options, scan patterns can be created from BMP image files and a novel edge-following algorithm can create scan patterns optimised for conformal scanning of complex structures (Grime et al., 2019).

Sample stage control: Interfaces to a range of sample stage control hardware including Aerotech, Smaract, Galil and PI. Control of up to six motion axes (linear or rotation) with position saving and the option of 2-D mapping using any two axes.

Automation: A wide range of run automation options including run lists generated by hand or from a control file, step and repeat map tiling of large areas, angular rotation sets for tomography or stereo pairs, Z-stacks for depth profiling.

Data processing: User-friendly interface to GUPIXWIN (separate licence required), RBS simulation and fitting using updateable non-Rutherford cross sections. Automated RBS correction of PIXE results and configurable spreadsheet output. A wide range of map image processing options including stereo anaglyphs. OMDAQ listmode files are compatible with GeoPIXE and GUMAP.

A demonstration version of OMDAQ can be downloaded here.

G.W. Grime et al. (2019) A simple edge-following scanning algorithm for proton beam writing and other direct-write lithographies - https://doi.org/10.1088/1361-6439/aafa03
SESSION III
Applications: Life Sciences (Biology and Medicine)
Chairs: Johnny Dias and Jiro Matsuo

Invited talks

1057-RADIOBIOLOGICAL AND MEDICAL RESEARCH AT THE ION MICROPROBE SNAKE

Judith Reindl ¹, Katarina Ilicic ², Stefanie Girst ¹, Matthias Sammer ¹, Christian Siebenwirth ³, Günther Dollinger ¹

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The superconducting nanoprobe SNAKE (Superconducting Nanoscope for Applied nuclear (Kern-) physics Experiments) is used to focus 10 MeV – 25 MeV protons and heavy ions (e.g. 55 MeV carbon ions or 33 MeV lithium ions) to sub-micrometer spot sizes using a set of three superconducting lenses. Focused protons are used to perform material analysis with proton-proton scattering. Furthermore, the high energies and the various kinds of ions are ideally suited to irradiate cells, tissue sheets and even live animals to address topics in radiation biology and medicine. This talk will focus on the technologies and experiments used for radiobiological and medical research. For this the samples are mounted on an epifluorescence microscope placed behind the beam exit nozzle. The beam can be deflected in a field of 500 µm x 500 µm size using two sets of electrical scanning units, for x-direction and y-direction, in front of the lenses. A defined number of ions can be applied to each irradiation point, by counting them behind the sample using a PMT. After the required number of ions is applied, the beam is switched of, using an ultrafast high-voltage switch. To irradiate large cell numbers, i.e. several thousand cells, the single fields are stitched together by moving the sample with the microscopy stage. Furthermore, the setup can be used to irradiate sub-cellular structures in living cells with an accuracy in the range of 1 µm. Using this setup it is possible to image, track and analyze the cellular response to radiation damage. The main obstacle of this is that only several tens to hundreds of cells can be targeted. To investigate long term cell survival, the gold standard in radiobiology, a live cell setup was established, which allows to follow the cells for several days post irradiation. With this the migration, proliferation and also cell death via apoptosis or necrosis can be analyzed.
**1053-Key contributions of ion beam imaging techniques to plant ionomics**

*Katarina Vogel-Mikuš* 1,2, Paula Pongrac 1,2, Marjana Regvar 1, Primož Vavpetič 2, Mitja Kelemen 2, Primož Pelicon 2

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Ion beam imaging techniques have considerably increased the knowledge about the uptake and accumulation of trace elements in plants. Understanding metabolic processes of trace element uptake, accumulation and compartmentation in plants is crucial in many aspects of our activities, from the selection of nutritious foods to the restoration of the environment. In this lecture, the most important findings obtained using ion beam imaging techniques (micro-proton-induced X-ray emission) will be presented, namely the mechanisms of accumulation and tolerance of trace metals in selected (hyper)accumulator and excluder plants, mycorrhiza and important crop plants.

**1056-In situ detection and single cell quantification of metal oxide nanoparticles using nuclear microprobe analysis reveal nano induced cellular ion homeostasis alterations**

*Hervé Seznec* 1, Philippe Barberet 1, Guillaume Deves 1, Laurent Plawinski 1, Claire Michelet 1, Marie-Hélène Delville 1, Marina Simon 1, Giovanna Muggiolu 1

CNRS, U. Bordeaux CENBG Gradignan-France 1

Chemical element imaging and quantification at the micrometer scale are often required to study the impact of exogenous compounds in living cells. This can be achieved by implementing analytical techniques on ion microbeam lines. The combination of several of these techniques such as Particle Induced X-ray Emission (PIXE), Rutherford Backscattering Spectrometry (RBS) and Scanning Transmission Ion Microscopy (STIM) enables both the detection, localization and quantification of the chemical composition at the cellular level. This presentation will show how these micro-analytical techniques, correlated with complementary optic and bio-analytical techniques, can bring more insight in the study of cellular homeostasis at the single cell level. A particular focus will be made on both in vitro (human cell lines) and in vivo (Caenorhabditis elegans) studies related to the impact of titanium dioxide nanoparticles (TiO2 NPs) on cellular ion homeostasis. First, we will illustrate that µ-PIXE can quantify how nanoparticles internalization influences in vitro the endogenous cellular content variation of some specific ions such as Ca\(^{2+}\), and that this variation can be correlated to an endoplasmic reticulum stress-dependent toxicity1,2. Second, we will present our last observations related to in situ and in vivo analyses conducted on Caenorhabditis elegans exposed to TiO2 NPs. µ-PIXE was found to be suitable for both accurate description of chemical structure of multicellular systems and for the detection of NPs. µ-PIXE revealed that the calcium and potassium homeostasis were deeply modified in the proximal intestinal cells in absence of NPs internalization. These observations would help to understand how ingested (but not internalized) NPs could lead to adverse effect on nematode development.
1067-Analyzing Individual Neurons in a Large Area Scan With a High Efficiency X ray Detector

Tilo Reinert 1, Malte Brammerloh 1, Markus Morawski 2, Primoz Pelicon 2, Primoz Vavpetič 2, Carsten Jäger 1, Thomas Arendt 3, Jan Meijer 4, Nikolaus Weiskopf 1, Evgeniya Kirilina 1

MPI for Human Cognitive and Brain Sciences Department of Neurophysics Leipzig-Germany 1 Jožef Stefan Institute Department of Low and Medium Physics Ljubljana-Slovenia 2 University of Leipzig Paul Flechsig Institute of Brain Research Leipzig-Germany 3 MPI for Human Cognitive and Brain Sciences Felix Bloch Institute for Solid State Physics Leipzig-Germany 4

Since iron is an essential ion for the physiology of brain functions but also connected with brain aging and neurodegeneration, it became one of the key interests for the development of quantitative magnetic resonance imaging (qMRI) which evolves as a new tool for brain research and neurodiagnostics. Therefore, we need to understand how iron, its micro- and nanodistribution contribute to the contrast in MRI.

We combined PIXE quantitative element mapping and high resolution quantitative MRI by analyzing the same regions in ex-vivo human brain. PIXE mapping was done on individual neurons as well as on large area scans. To improve sample throughput and map quality especially for iron maps at generally low physiological concentrations we installed a high efficiency arrangement of four SDD-detectors with a combined solid angle of 1.2 msr. The new detector set-up enables the analysis of individual neurons in a squaremillimeter-size scan area with micron resolution. As an example we show the analysis of about 200 neurons contained in a single scan with a 5-hour detection limit for iron below 10 ppm for single cell analysis.

Based on the PIXE-data, a qMRI model could be derived that provides a measure for neuronal density and iron concentration in the substantia nigra as a biomarker which is sensitive to early pathological changes in Parkinson’s disease.

Contributed talks

1055-The dynamics of XRCC1 in complex DNA lesions caused by high energy heavy ions irradiation

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DNA damage repair is crucial to maintain the stability and integrity of human genome. XRCC1 is one of the key proteins in DNA damage response, which plays an important role in the DNA base excision repair (BER) pathway and the microhomolog-mediated end joining (MMEJ) pathway. The structure and function of XRCC1 have been extensively studied over the past years. However, the further research in this field is still needed, which could put forward some new ideas as well as new insights into the repair mechanism of DNA damages especially induced by the ionizing irradiation. The dynamics of XRCC1
in complex lesions caused by high energy heavy ions irradiation have been studied with the live cell imaging system based on high energy heavy ion microbeam facility in the Institute of Modern Physics (IMP, CAS). The relative fluorescence intensity of foci can be acquired by analyzing the time-lapse images captured with second resolution, and the recruitment rate constant and dissociation rate constant of the DNA damage repair proteins can be obtained by fitting these relative fluorescence intensity curves. When HT1080 cells (XRCC1 tagged with RFP) were irradiated with 86Kr ions twice with an interval of 100 s. The dissociation rate constant of foci induced by the first irradiation is about two times than that of foci caused by the second irradiation, illustrating that many XRCC1 molecules dissociate faster than usual and are forced to move to the newly generated damage sites. There may be an emergency measure, which will repair the more serious damages preferentially. The recruitment of XRCC1 to the nascent DNA damage sites is significantly quicker than old ones, and this may because the repair pathway has been activated and some preparatory work has been completed after the previous irradiation. Besides, cells in different cell cycles were also irradiated. The recruitment rate constant of G2 phase cells is significantly larger than that of G1 phase cells. DNA replication is accomplished in G2 phase cells, and the same irradiation can cause double DNA damages. Thus, the attraction to the repair proteins is getting bigger in G2 phase cells and the recruitment is faster. The dissociation rate constant of G2 phase cells is lower because it takes a longer time to repair the more damages. Furthermore, by analyzing the cells irradiated by different numbers of ions, we found that the recruitment rate constants are basically the same, but a single repair focus can recruit more protein molecule when the number of irradiated ions is smaller, and it need less time to finish the repair. The results can contribute to study the repair mechanisms of clustered DNA damages induced by high energy heavy ions radiation. They also provide a good reference and guidance for radiation therapy and space radiation protection.

1038-Quantitative nanoscale imaging of nanodiamonds in whole cells with correlative ionoluminescence and scanning transmission ion microscopy

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Nanoscale imaging in whole cells is essential to observe cellular functions, interactions and dynamics in the native state of the cells. To this end, super-resolution fluorescence techniques, such as stimulated emission depletion microscopy, have become enabling tools to image whole cells of labeled constituents. To link the labeled cellular components with the underlying ultrastructure, the super-resolution optical methods have been combined with electron microscopy to provide correlative light-electron imaging capabilities. However, electrons essentially suffer from significant scattering when interacting with biological samples as thick as a whole cell, which in turn compromises the resolution. As a result, correlative super-resolution imaging of whole cells remains difficult.
In this talk, we present a straightforward nanoscopic approach for whole-cell correlative imaging, by simultaneously performing ionoluminescence and scanning transmission ion microscopy with a highly focused beam of alpha particles. By collecting alpha-particles-induced photons, we can perform luminescence imaging of a cell that has uptaken nanodiamonds as imaging probes. Simultaneously, by measuring the energy loss of the alpha particles that transmit through the cell sample, a density map rendering cellular ultrastructure can be obtained. We also describe the mechanism of ionoluminescence in nanodiamonds, indicating the advantages of this type of probes used for ion beam imaging. Lastly, we propose the use of this approach in radiobiology where information extracted from single cells can give valuable information underlying enhanced radiosensitivity in cancer therapy.

1054-Application of track etched nanopore in biomolecules detection

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Institute of Modern Physics Chinese Academy of Sciences LanZhou-China 1

Many emerging applications of nanopore detection such as proteins, RNA, and DNA have been reported, in which the size and structure of the biomolecules are detected by the block current when they transport through a single nanopore[1]. The smaller the size of the nanopore is, the higher the detection accuracy will be obtained. Nanochannel fabrication using the latent track of high LET heavy ions in solids has the advantage of precise pore geometry control and pore production. Compared with solid nanopore fabrication by drilling in silicon nitride membrane, polymeric nanopore using ion track etching technique can reduce both the material and fabrication cost. We produced different shape nanopores like conical, double conical, and cylindrical by controlling etch solution[2], and in our study, we fabricated small nanopore(< 5nm) and detected DNA molecules by double conical PET nanopore. Our study expanded the application of track-etched nanopores to detection and provide a new idea for the application of heavy-ion micro-nano processing.

1031-Study of prosthesis degradation under particle induced x-ray emission (PIXE) and X-ray absorption. Preferential leaching of specific aluminum chemical state.

Esther Punzón-Quijorna 1, Mitja Kelemen 2, Primož Vavpetič 2, Iztok Arčon 2, Rajko Kavalar 3, Samo K. Fokter 4, Primož Pelicon 2

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Ti-6Al-4V alloy, initially developed for aerospace applications, is currently the most widely used titanium alloy for surgical implants. However, the potential release of V and Al, with toxic effects and, in the case of Al, a possible connection with neurological disorders [1] [2], must be further studied. When a prosthesis is implanted into the body, it is exposed to a complex electrochemical system. The
Acidity may increase around the implant due to the inflammatory response of surrounding tissue creating a corrosive environment for metallic implants. Defects on the prosthesis surface or the presence of mobile parts may induce point corrosion, fretting or galvanic corrosion on the prosthesis. This may bring the release of metallic debris to the surrounding tissue and trigger a cell reaction cascade leading to prosthesis rejection. In addition, the accumulation of metals in elderly patients, main users of prosthesis, is cause of concern as they are more prone to accumulate metals due to a dysregulated metal homeostasis [3].

At TissueMaps project we have analysed the presence of metallic debris after a hip endoprosthesis failure for 12 clinical cases. The study has been carried out by using Particle Induced X-ray Emission (PIXE) as main technique, combined with other techniques as X-ray Absorption Spectroscopy (XAS). Special attention was paid to the behaviour of Al. Our experiment set up allows to detect light elements from Na. Previous works revealed a preferential leaching of Al [4] [5]. We present the results from PIXE and XAS analysis from two clinical cases where the Al contribution is coming from a metallic alloy (Ti-6Al-4V) and Zirconia toughened Alumina. This allowed us to conclude that the low amount of Al in some clinical cases is due to a preferential release of specific chemical states of Al debris.


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1066-MeV ion microbeam development and research at the Louisiana Accelerator Center

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The Louisiana Accelerator Center is a user research-outcome driven research center that operates two MeV ion microbeams of Oxford triplet configuration. One (μB1) is currently dedicated to imaging while the other (μB2) is operated as an ultralow flux ion irradiation facility. μB1 has standard ion beam analysis capabilities, PIXE, RBS, off- and on-axis Scanning Transmission ion Microscopy (STIM) and an automated x-y-z sample stage. A major effort is directed towards construction of MeV SIMS using a time of flight (ToF) Reflectron mass spectrometer. The start pulses are derived from the direct-STIM detector (doubly shielded to allow accurate timing without spurious pickup). The molecular ions are accelerated and focused on the Reflectron multi-channel plates using a gridded snout on an einzel lens. To maintain a high collection efficiency and fast scan speeds, an electrostatic beam blanker and a novel time-stamping multi-stop time to digital convertor are under development. The development of the imaging microbeam has been driven by research programs successfully used in studying the build-up of sulphur in a novel Ca–Fe based catalytic scavenger for de-sulphurisation of natural gas where it was shown that the S is scavenged by the Fe rich phase. In another study, heavy elements have been studied in the gut tissues of rhesus macaques infected with simian immunodeficiency virus. (Monkey analogue of HIV.) Large perturbations in heavy elements were seen between infected and control animals. Remarkably, concentration hot-spots for many elements were observed including Pb in archived samples. These were likely associated with particles in the chymus. (Pb originating from paint ingestion.) μB2 has been used to study attachment and detachment of gravity sedimented lymphocytes from rhesus macaque peripheral blood and the prostate carcinoma Du145 cell line that exhibited an increase in granulation from irradiation. This method allows for irradiation of vertically placed tissue cultures using a horizontal beam.


1042-Differential distribution of macro and microelements in leaves of two olive (Olea europaea L.) varieties

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In accordance to their roles in plants, mineral elements are differentially distributed between different cell types and leaf tissues. They provide structure to membranes, act as enzymatic co-factors and constitute important macromolecules. Adequate conveyance and allocation of elements throughout the leaf ensures continuation of fundamental metabolic processes.

Olive (Olea europaea L.) is one of the most important fruit crops in the Mediterranean area, exhibiting high varietal diversity throughout the basin. The main objective of this trial was to determine the distribution of macro- and microelements (potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), sulphur (S), chlorine (Cl), iron (Fe), zinc (Zn), and manganese (Mn)) in leaf cross-sections of Istarska bjelica and Leccino olive varieties, using multi-elemental, micro-particle induced X-ray emission (micro-PIXE) technique.

With an exception of Ca, concentrations of leaf K, P, Mg, S and Cl did not differ significantly between the two varieties, amounting to 24.51, 1.54, 1.37, 0.88, 1.29 g kg⁻¹ dry weight (DW) for Istarska bjelica and 22.93, 1.37, 1.75, 0.95, 1.15 g kg⁻¹ DW for Leccino respectively. Potassium was largely allocated at the palisade mesophyll of both varieties, however high K concentrations were also determined at the spongy mesophyll, beneath the main vasculature. Phosphorus ions mainly surrounded vascular tissues and to a lesser degree accumulated in the palisade mesophyll of both varieties. Highest Ca concentrations were detected in epidermis, followed by a high allocation around vascular tissues of both varieties. Leaf Ca concentration was significantly higher in Leccino (8.07 g kg⁻¹ DW) than in Istarska bjelica (5.55 g kg⁻¹ DW). Magnesium was evenly dispersed in leaves of both varieties, whereas S predominated in the palisade mesophyll and Cl accumulated mainly around the bundle sheath cells. Microelements were evenly distributed throughout the leaf cross-sections of both varieties, recording no significant differences in their leaf concentrations.
1046-Elemental composition of alligator eggshell and eggshell membrane using micro-PIXE

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Over the past years there has been a notable lack of success with regard to breeding Alligator mississippiensis in alligator breeding facilities. Captive alligator eggs exhibit a much lower hatch rate (<50%) in comparison with wild alligator eggs (=90%). Additionally, the hatch rates of the alligator eggs decrease in captivity until zero production is reached. The fertility of eggs within clutches also show similar trends. This decline in production has been documented in over a twenty-year study at the Rockefeller Wildlife Refuge [1]. The lack of reproductive performance is attributed to the maternal diet and transfer of nutrients to the egg. Previous investigation on the eggshell and eggshell membrane of these reptiles lack comparisons between feed groups [2]. In this study, the elemental compositions of the eggshell and eggshell membrane of Alligator mississippiensis from wild and captive groups consisting of two different commercially manufactured feeds were investigated using micro-PIXE. Comparisons between fertile eggs and infertile eggs originating from same clutches showed that the major elements of the eggshell included calcium and aluminum, and that of membrane included sulfur and chlorine. However, the elemental distributions between the test groups were heterogeneous, which may have correlation to poor reproductive performance.


1061-Distribution of mineral elements along a plant leaf

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The current understanding of tissue-specific element distribution in plants has been assembled from a single and often randomly selected cross sections from an organ [1,2], predominantly acquired in a qualitative manner only, not considering gradients in element concentrations as the tissue arrangement changes along the plant organ. Therefore, it has been impossible to argue that the selected cross-section is representative of the whole organ making conclusions difficult and in need of further validation. Considering that in a heterogenous samples elements are not evenly distributed [3,4] the aim of this study was to determine tissue-specific distribution of mineral elements along a leaf of spinach (Spinacia oleracea L.), because spinach leaves has unusually great concentrations of Ca and Mg [5]. However, spinach is characterised by great concentrations of oxalic acid, one of the key antinutrients which limit Ca and Mg
bioavailability in our diets. Oxalic acid is an organic acid that exists as free acid or as mineral crystal that includes soluble salts of K, Na and Zn, and insoluble salts (oxalates) of Ca, Mg and Fe. Oxalate crystals are the main constituent of urinary stones [6]. Two spinach genotypes differing in Mg concentrations were evaluated. Leaves were frozen in liquid nitrogen using metal-mirror freezing approach and freeze-dried as described previously [7]. Cross sections along the leaf length were made using Pt-coated razor blades, mounted onto double sided carbon tape and analysed with the nuclear microprobe at Jožef Stefan Institute. Spectra were fitted, and quantitative distribution maps were generated using GeoPIXE software [8]. Calcium, but not Mg was associated with oxalate crystals. While there was not much variability in Ca distribution with 20-50 μm Ca-oxalate crystals being distributed homogeneously along the leaf length, there was both vertical and horizontal gradient in Mg concentration. Acquiring data on mineral element distribution in a whole organ will have consequence in enhancing understanding of element transport and dynamics in plants.
The lithium-ion technology holds a prominent place in the battery's area. Although its energy densities increased and cycle life raised as high as thousands of cycles, it still needs vast improvements to meet ever-greater demands regarding autonomy, lifespan, safety and miniaturization. Capacity fading during cycling remains a major problem limiting battery lifetime. It is therefore necessary to understand the origin of aging phenomena leading to loss of electrochemical performance in order to guide research towards new materials. For this, many in situ / operando studies have been developed (XPS, MET, NMR, XRD,…). However, none of the techniques mentioned can directly detect the lithium element, which makes the visualization and quantification of the whole lithium present in an electrode or a battery impossible. Nuclear microanalysis is a technique capable of giving quantitative and qualitative information on spatial distributions of light elements such as lithium. It is therefore a tool with great potential for understanding the operating mechanisms of lithium insertion materials.

In previous ex situ studies, we showed immobilization of lithium in the LiFePO4 electrode during the first charge / discharge cycles. We further developed an electrochemical cell coupled to the nuclear microprobe to perform in situ / operando analyzes. The cell is capable of providing electrochemical performances comparable to those obtained with conventional electrochemical cells on the first two cycles. We thus observed operando in a LiFePO4-graphite assembly the formation of a SEI layer (Solid Electrolyte Interface) and the trapping of lithium at the LiFePO4 // LiPF6 interface.
1028-Fluorescent Defect formation in wide bandage semiconductor by utilizing particle beam writing technique

Wataru Kada 1, Taisei Higuchi 1, Moriyoshi Haruyama 1, Yoshinori Suda 1, Yasuyuki Ishii 2, Shinobu Onoda 2, Takeshi Ohshima 2, Kenta Miura 1, Osamu Hanaizumi 1

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Focused proton/particle microbeam is considered a powerful tool for rapid material modification and prototyping of unique microstructures of various materials. In previous studies, proton/particle beam writing (PBW) techniques successfully demonstrated microfabrication of high-aspect-ratio structures that have been developed by processing polymer materials and photoresist materials. Also, we have successfully manufactured integrated optical devices i.e. Mach-Zehnder waveguides based on polymer thin films of PMMA or PDMS (Kaneko et al., 2019, Kada et al., 2015, Sakai et al., 2013). By utilizing the characteristics of high straightness of particle beams with the MeV energy range, it should be possible to process new functional structures in materials with limited workability. Recently, we are applying PBW technology to form microscale fluorescent centers in wide bandgap semiconductors including silicon carbide and diamond. Creating fluorescent defects at desired positions and structures should be key and plays an important role in the development of quantum devices. There are already examples of studies on fabrication of graphite structures which has been already successfully demonstrated in diamond (i.e. Bosia et al., 2011). The desired density of fluorescent defects could be formed by optimizing beam fluence and related irradiation conditions. Our recent trial successfully provided the evidence of the applicability of PBW technologies to form desired VSi defects in silicon carbide (SiC) by utilizing focused protons with energies up to 3 MeV, from 3 MV single-ended accelerator placed at QST, TARRI. A three-dimensional micrometer-scale processed layer of VSi was able to be controlled by changing the energy of focused protons (Kraus et al., 2017). Furthermore, it was possible to introduce defects in diamond that could be assumed to be categorized as GR-1 by introducing defects with the same proton microbeam setup with different irradiation parameters. Heavy-ion microbeam was also able to be utilized for PBW on the diamond and it was possible to confirm the formation of NV centers by irradiation of nitrogen or recombination of generated defects with residential nitrogen. Some applicational devices could be expected to be developed by combining the results of appropriate temperature control and observation with a confocal microscope after the irradiation. Results indicated that PBW would be utilized in the futuristic microfabrication of wide bandgap semiconductors for quantum material applications, by combining the use of other ion beam material modification technologies as well as other material process technologies.

A part of this work was supported by MEXT/JSPS Grant-in-aid for scientific research JP16K13721.
1049-Fully 3D scCVD diamond microdosimeter and its charge transport properties studied with IBIC technique

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Hadron therapy is an innovative mode of radiotherapy for cancer treatment. Its advantages are of both physical as well as biological nature. Alongside the physical advantages as precise dose delivery due to the nature of the ions stopping power, ion beams additionally show an increased relative biological effectiveness (RBE). RBE is defined as the ratio of the irradiated dose of ions to that of a reference photon energy that would be required to result in the same biological effect for both. For treatment planning, a reliable estimation of RBE of such ion beams to irradiated tissue is required. The access to experimentally measured quantities required for the RBE estimation is essential but there is a lack of practical experimental tools. To address this issue, we are developing a new microdosimetric system based on scCVD diamond membrane sensors. Our recently fabricated microdosimeter prototype is fully 3D sensor based on completely isolated multiple micro-Sensitive Volumes (µSVs) of 20 μm in diameter and 10 μm thickness, embedded in non-electrically active resin. The charge transport properties of such fabricated 3D sensor were studied with the Ion Beam Induced Current (IBIC) technique at CENBG Bordeaux and RBI Zagreb, giving an insight into the performances of the sensor in well-controlled conditions as well as its response to the various projectiles with large span of the LET. Obtained results shows that 3D diamond prototype could fulfil severe requirements for solid-state microdosimeter in hadron therapy in terms of charge collection, microSVs geometrical definition, LET response linearity and radiation hardness. As a next step, sensor’s characterization coupled to dedicated electronics is planned in clinical proton beams at hadron therapy facilities.

Contributed talks

1012-Applications of the Sirius microprobe of ANSTO for testing micron sized sensitive volumes in prototype soi and CVD detector structures developed for radiation therapy

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Microdosimetry is a study of the effect of radiation on cellular sized structures, excellent microdosimeter should have well defined sensitive volume (SV) for accurate definition of mean chord length value and perfect charge collection efficiency. In this work, we present recent applications of the SIRIUS microprobe of ANSTO for charge collection characterisation of silicon and diamond microdosimeters developed by the CMRP, University of Wollongong and CEA-LIST, France, respectively. The reduced-rate H, He, C and O
ion microbeams with energies in the MeV range and sub-micrometre spot-sizes were scanned over silicon on insulator (SOI) mushroom microdosimeters with 5 µm and 10 µm thick active layer and CVD diamond microdosimeters and the charge collection median energy maps were obtained. The same characterisation was performed on two different prototypes of single crystal CVD diamond-based microdosimeters, including the boron-doped self-biasing p+ sensor and more universal and externally biased diamond GR sensor. High resolution CCE distribution mapping allows i) functionality testing in different operating (biasing) conditions applied to a device and ii) further optimisation of design by determination of the charge carrier transport properties and the energy deposited by incident ionising radiation in a particular device. IBIC technique using SIRUS microprobe at ANSTO is extremely useful for characterisation of semiconductor radiation detectors to be used in various applications including radiation therapy as well as terrestrial and space radiation protection.

1017-Nanoscale ion implantation using focussed highly charged ions

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At the Leibniz Joint Lab “Single Ion Implantation” we investigate methods to realise deterministic single ion implantation for quantum technology applications. For the detection of single ions in an image charge detector, highly charged ions (HCIs) significantly enhance the sensitivity, since the signal is proportional to the charge [1,2]. Hence, a focussed beam of highly charged ions is necessary for our approach to realise well-controlled single ion implantation. To fulfil these requirements, we set up a focussed ion beam (FIB) based ion implanter equipped with an electron beam ion source (EBIS) [3]. The ion optical system was optimised and characterised via secondary electron imaging. On the sample surface, the smallest measured foci are below 200 nm, with objective aperture diameters of 5 and 10 µm, showing that nanoscale ion implantation using an EBIS is feasible. As an example of its utilisation, we demonstrate the generation of nitrogen-vacancy centres by annealing after introducing local vacancies in diamond using focussed, mask-less irradiation with Ar8+ ions with sub-micron three-dimensional placement accuracy. This new ion implanter enables the use of HCl relevant for single ion implantation and other surface treatment techniques. Furthermore, through the selection of different charge states, kinetic energies from a few to several hundred keV are accessible in a comparably compact set-up.

1029-Diamond single ion detectors for shallow colour centre array engineering

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The ability to deterministically implant dopant atoms in diamond enables the engineering of ordered colour centre arrays for advanced quantum computing, sensing and imaging applications with room temperature compatibility. We aim to adapt and apply our deterministic silicon doping technique to diamond substrates and address the critical role of surface recombination effects on the single ion detection confidence.

When an ion strikes into a diamond crystal, its deceleration process is subject to nuclear and electronic stopping mechanisms. The latter causes creation of free electron-hole (e-h) pairs, which can be detected as a charge-proportional voltage pulse via integrated surface electrodes. However, due to the wide bandgap of diamond compared to silicon, the number of ion-induced e-h pairs – and thus the related signal pulse - is considerably lower. To ensure a high charge collection efficiency (CCE), and in turn a sufficient single ion detection confidence, it is crucial to eliminate excessive e-h pair recombination effects.

Here, we demonstrate a combined iterative computational-experimental approach of our diamond single ion detector development strategy. A COMSOL finite element model is therefore first applied to evaluate competing surface- and bulk recombination effects and to optimize the detector design accordingly.

Ion Beam Induced Charge (IBIC) maps, acquired with a scanning 1 MeV He+ nuclear microprobe, confirm computational predictions and indicate the need for a trenchled lateral surface electrode geometry for highest charge collection efficiency (CCE). Subsequently conducted IBIC tests using 14 keV H+ and H2+ ions, reveal a notably reduced CCE (30%) compared to MeV results (>90%).

This discrepancy is assigned to excess surface recombination effects. To mitigate this effect for application-relevant ion implant energies (< 30 keV), we address its origin and processing measures for the next device iteration.
1048-Bright near surface silicon vacancies color centers fabricated by helium ion irradiation at diamond nucleation surface
Chengyuan Yang 1, Zhaohong Mi 1, Huining Jin 1, Andrew Anthony Bettiol 1

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The negatively charged Silicon Vacancy (SiV-) color centers in diamonds have shown excellent optical properties (such as narrow spectral linewidth, short excited-state lifetime), and become a promising alternative to the widely studied nitrogen-vacancy centers for quantum technology. However, several fabrication issues limit the application of SiV- centers, for example, severer fluorescence quenching by Si implantation, poor Si to SiV- conversation yield, and the high material cost of single-crystal diamond. In addition, it is also crucial to fabricate SiV- centers close to the diamond surface in order to achieve an efficient coupling with photonic devices or a high sensitivity to the surrounding environment. Here we present a method to achieve scalable fabrication of bright near-surface SiV- centers by applying MeV Helium ion irradiation to the nucleation surface of a low-cost and widely available polycrystalline diamond film. Si atoms are incorporated at the diamond nucleation surface by growing the film on a Si substrate. After removing the substrate, the nucleation surface is irradiated by 1.7 MeV Helium ions, and then annealed at high temperature at high vacuum. We show that this process can create a layer of bright and uniformly distributed SiV- centers located at the diamond near-surface within a depth about 750 nm with minimal damage to the diamond structure. The effect of Helium ions on the formation of SiV- centers is also investigated by varying ion fluence, and the radiation damage to the diamond film is studied by SRIM simulation. The formation process of SiV- center by the Helium ion irradiation and the annealing process is discussed. This work opens up a new approach to fabricate large-scale SiV- center based quantum devices, which will benefit a wide range of applications such as thermometry, magnetometry, bio-sensing and imaging.

1063-Single ion implantation of bismuth using a new focused ion beam instrument
Nathan Cassidy 1, David Cox 1, Roger Webb 1, Ben Murdin 2, Paul Blenkinsopp 3, Ian Brown 3, Richard Curry 4

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The results from a focused ion beam instrument, designed to implant single ions with a view to the fabrication of qubits for quantum technologies, are presented. The difficulty of single ion implantation is accurately counting the ion impacts. This is achieved here through the detection of secondary electrons generated upon each ion impact. The implantation of single bismuth ions with different charge states into Si, Ge, Cu, and Au substrates is reported, and the counting detection efficiency for single ion implants and the factors that affect such detection efficiencies are determined. It is found that for 50 keV implants of Bi++ ions into silicon an 89% detection efficiency can be achieved, which is the first quantitative detection
efficiency measurement for single ion implants into silicon without implanting through a thick SiO2 film. This level of counting accuracy provides implantation of single impurity ions with a success rate significantly exceeding that achievable by random (Poissonian) implantation.

Posters

1033-Functionalization of microfluidic devices by microstructures created by proton beam lithography
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Microfluidic devices have become important part of technology nowadays in numerous fields of application, such as chemical reactions, biosensors, synthesis of nanomaterials, diagnostic device for detection of biological samples, etc. Thanks to their small dimensions, their surface to volume ratio is extremely high. Because of this, they offer unique physical characteristics, very different ones from the macroscopic world. At the same time, the Reynolds number of the fluid flow in them are typically below 1, so laminar flow dominates. This makes the mixing of two different fluid particularly difficult, and occurs only by diffusion. Therefore, the mixing is still a great challenge for researchers working with microfluidic devices. Due to this, one of their important field of research and development is mixing at microscale. Micromixer is a device which is used to mix two or more fluids in a micro scale channel to handle micro and nanoliter volume of fluids.

Generally, micro devices are created by UV-lithography using SU-8 master, moulding with poly(dimethylsiloxane)(PDMS) silicone polymer, which is then polymerized. The PDMS surfaces of the two parts of the microfluidic system are bonded by air plasma treatment after alignment.

As a new fabrication approach, PDMS microstructures were integrated into PDMS microdevices by combining proton beam lithography (direct writing technique utilizing focused, few MeV proton beams, to create microscale structures) and conventional UV lithography fabrication techniques. This way, the microstructures and the micro-devices can be made from the same material, which is not only useful, but in case of certain applications, it is essential (e.g. cell separation, etc.).

This work deals with the design of various microfluidic devices with and without integrated microstructures. The investigation involves the computer simulation and optimization, and the fabrication with the above mentioned methods. Finally, the analysis of the mixing efficiency of the micromixer devices was realized with UV/vis spectroscopy at different fluid flow rates. Compared to the small size of the whole mixing chip, very high mixing efficiency could be achieved.
1044-Use of Surrey Ion Beam Centre tandem analysis stations to measure elemental distributions in 3D nano structures

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State-of-the art nano-electronic devices, such as FinFETs, extend into the third, vertical dimension as the scaling of planar MOSFETs has reached its limit. Ion beam analysis of these and other three-dimensional nanostructures requires the use of novel detection and data analysis methods. In addition, such structures are often manufactured on wafers within a small die (typically ~250µm by 250µm) and therefore impose the use of focused analysis beams. Altogether, the ion beam analysis of the advanced nano-electronic structures brings new requirements on the ion scattering end-station design.

The Surrey Ion Beam Centre (SIBC) operates a 2MV tandem accelerator with one analysis station (“Nanobeam Chamber”) accepting a focussed micrometre sized ion beam typically used for PIXE mapping and a second end station (“Broadbeam Chamber”) usually accommodating a millimetre sized beam used for Rutherford back scattering (RBS) analyses using multiple detectors. This paper discusses the equipment challenges recently overcome at SIBC during the collection of multiple angle spectra of three-dimensional samples that have traditionally been too small to measure in the Broadbeam Chamber.

These developments are being performed within the framework of the European RADIATE Consortium [1] which promotes access to ion beam facilities. A Joint Research Activity (Work Package 22.2) is investigating the extraction of elemental distributions in three dimensional structures by collecting ion beam scattering data over different analysis geometries and analysing the data accounting for the non-planar nature of the substrates [2, 3].

[1]  https://www.ionbeamcenters.eu/
Metalloproteins comprise over one-third of proteins, with approximately half of all enzymes requiring metal to function. Accurate identification of these metal atoms and their environment is a prerequisite to understanding biological mechanism, but there are no routine analysis methods with the sensitivity and quantitative accuracy to do this.

In the late 1990s we developed microPIXE/RBS as a tool for quantifying metals in proteins using the known sulfur concentration as an internal standard and applying matrix corrections derived from the RBS data (Garman and Grime, 2005). We have now automated this process (using a dedicated module in OMDAQ) to permit unattended high throughput analysis of many samples deposited as 20µm diameter spots on thin polypropylene film by inkjet printing techniques.

We have demonstrated this method using two distinct sets of 30 proteins identified as metalloproteins in the Protein Data Bank (PDB) (Grime et al, 2019). In each case we have found that over half of the metals had been misidentified in the deposited structural models. Some of the PIXE-detected metals not seen in the models were explainable as artifacts from promiscuous crystallization reagents. For others, using the correct metal improved the structural models and identified new functionality.

This is a highly significant finding. The PDB is a critical resource for researchers worldwide. In 2017, there were on average 1.86 million downloads per day in the US alone which suggests that over 350,000 models downloaded per day may not contain the correct metal. This has profound implications for those using the models, whose understanding of them may therefore be flawed.

This talk outlines the method and summarises the initial findings.


1030-PIXE with 3.5 MeV protons for the study of low elemental concentrations in biological tissue
Maria Dolores Ynsa 1, Joan Ripoll-Sau 1, Thomas Osipowicz 2, Mark B. H. Breese 3, Minqin Ren 3

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The onset and progression of many degenerative diseases have been shown to be directly linked to the presence or absence of certain metal ions. Consequently, the detection and quantification of these ions in tissues (healthy and during disease development) may improve the understanding of the driving pathophysiology. However, some metal ions show low concentrations in biological tissue and their detection and exactly quantification is not a simple undertaking. In this work, low Cu concentration is determined using PIXE with a 3.5 MeV proton beam in biological tissue, in particular, in atherosclerotic rabbit tissue. We find that the atherosclerotic lesion areas of animal models from animal groups fed with 1) High Fat Diet (HFD) and 2) Zinc-rich diet, respectively, show lower Cu levels than those in the arterial wall areas as well as the artery of the control animal models. Fe and Zn concentration values obtained with 3.5 MeV proton beam confirm the previous results of these elements in atherosclerosis. The results confirm that PIXE with high-energy protons is a good analytical technique for the quantification of low metal ions in biological tissue.

1009-MeV TOF SIMS in the organic material analysis applications in cultural heritage biology and forensics
Zdravko Siketić 1, Iva Bogdanović Radović 1, Matea Krmpotić 1, Marko Barac 1, Marko Brajković 1

Ruder Boskovic Institute Division of Experimental Physics Zagreb-Croatia 1

The MeV Time-of-flight Secondary Ion Mass Spectrometry (MeV TOF-SIMS) technique is based on a concept being developed already in 1974 when the first papers on desorption of molecular ions using fission fragments from 252Cf source (plasma desorption mass spectrometry – PDMS) appeared. It has been demonstrated that several orders of magnitude larger yields, as well as less fragmentation, are expected for larger molecular masses when MeV ions are used for the excitation,
which is especially important for imaging of organic samples with a micrometre lateral resolution. In 2012, the MeV TOF-SIMS setup is constructed and installed at the Ruđer Bošković Institute Heavy Ion Microbeam Facility in Zagreb. Due to the technique potential to analyse high-masses with high-sensitivity, and the fact that it is surface sensitive, MeV TOF-SIMS was employed for the analysis of the various organic samples from the cultural heritage, biology, and forensics. MeV TOF-SIMS setup was successfully applied for cultural heritage studies, namely for the analysis of the modern paint materials and for distinguishing between different forms of pigments and binders with molecular masses in the range from 1 - 1200 Da. Capabilities of the MeV TOF-SIMS technique were also demonstrated by measuring chemical composition (2D lipids distributions) inside the individual CaCo-2 cells as well as within the mouse liver and brain tissue. Recently, MeV TOF-SIMS in combination with Particle Induced X-ray Emission (PIXE) was applied to determine the deposition order of the different writing tools for forensic document examination. In addition, the latest results on the applications of the new MeV TOF-SIMS setup, with glass capillary for the ion beam focusing, will be presented.

Contributed talks

1035-New ion micro beam analysis results in provenance determination of archaeological Lapis lazuli
Laura Guidorzi 1, Alessandro Re 1, Alessandro Lo Giudice 1, Alessandro Borghi 2, Leila Es Sebar 3, Valentino Rigato 4, Leonardo La Torre 4, Davide Carlucci 4, Dennys Frenez 5, Massimo Vidale 6
Università degli Studi di Torino Department of Physics Torino-Italy 1 Università degli Studi di Torino Department of Earth Sciences Torino-Italy 2 Politecnico di Torino Department of Electronics and Telecommunication Torino-Italy 3 INFN - Laboratori Nazionali di Legnaro AN2000 Legnaro-Italy 4 Università di Bologna Department of History, Cultures, Civilization Ravenna-Italy 5 Università degli Studi di Padova Department of Cultural Heritage: Archaeology and History of Art, Cinema and Music Padova-Italy 6

Archaeological evidences show that the Badakhshan Province (Afghanistan) is the most plausible hypothesis, if not the unique, for the provenance of lapis lazuli used in antiquity. To confirm such assumption, a protocol to identify the provenance of the raw material has been proposed and successfully applied to lapis lazuli archaeological and artistic objects [1,2]. The protocol is mainly based on a comparison of the physico-chemical properties of rocks of known provenance with archaeological finds and historical objects, obtained by means of Ion Beam Analysis (IBA) techniques. In particular, micro-PIXE and micro-ionoluminescence (IL) were used to detect trace elements and characteristic luminescence of some rock-forming minerals in lapis lazuli, specifically diopside, wollastonite and pyrite. The micro-scale of the beam is needed for the micrometric size of the crystals under investigation. In this work the last results on new archaeological samples from the important site of Shahr-i-Sokhta [3], located in eastern Iran and dated back to the 3rd millennium BCE, are presented.
A first group of six small samples from Shahr-i-Sokhta site have been analysed and underwent the protocol; these were part of the manufacturing waste, so it was possible to cut them to expose the core, untouched by weathering agents. IBA measurements were carried out on 13 diopside and 9 pyrite crystals. The analyses have been performed in vacuum at INFN-LNL (Legnaro, Padova, Italy) with 2 MeV protons.

Wollastonite was not observed. Moreover, analyses on diopside crystals have shown a high content of Ti, V and Cr and a low content of Sr. Finally, pyrite crystals, that are not significantly altered, have a low Cu/Ni ratio. On the basis of these results and taking into account the protocol for provenance determination, the Shahr-i-Sokhta samples were preliminarily attributed to an Afghan origin.


1024-Total IBA detailing mineralising fluid migration and exsolution to form porphyry copper deposits

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Porphyry deposits are of global economic significance as our main source of Cu and Mo, and as a major provider of Au and other important metals (Sillitoe, 2010). Although much is known about these magmatic-hydrothermal ore deposit systems (e.g. Richards, 2005; Seedorff et al. 2008; Sillitoe 2010; Wilkinson 2013; Richards 2016), it is unclear how metals are transported by fluids from their magmatic source into the porphyry-forming environment. This is mainly because suitable, vertically extensive, sections through the upper parts of porphyry systems, from large (4-7 km depth) magmatic bodies through to surface volcanics, are rare (Seedorff et al., 2008). An exception is the archetypal Yerington porphyry district, Nevada, where a ca. 8 km deep section has exposed surface volcanics, three major plutons, hundreds of dykes and four known porphyry deposits (Dilles, 1987). The district consequently provides fundamental constraints for models of porphyry-forming systems. From Yerington, our new field, textural and geochemical evidence shows that the main conduit and local source of mineralising fluids was aplite dykes. Further, we use SEM-CL, EPMA and Total-IBA to characterise multiple generations of mineralising fluid flow though these dykes, particularly through measurements of titanium in quartz. This unveils an interconnected late hydrothermal quartz network which reflects palaeo-permeability through a magmatic crystal mush of
feldspar and quartz. This permeability allowed the flow of mineralising fluids from relatively evolved internal regions of the underlying Luhr Hill granite pluton (unobserved), to form copper-containing miarolitic cavities and subsequently porphyry-type deposits above. The mechanisms detailed by these data can explain the narrow focusing of mineralising fluids and high fluid/rock ratios necessary to form porphyry deposits. This has significant implications on our understanding of porphyry deposit formation, as well as other ore systems and volcanic processes.


1069-Biological and environmental materials microanalysis at the University of North Texas
Todd A. Byers 1, Cory Nook 1, Mostafa Ibrahim 2, Alexandra G. Ponette-Gonzalez 3, Khaggeswar Bheemanapally 2, Karen P. Briski 2, Bibhudutta Rout 1, Gary A. Glass 1, 9

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The Ion Beam Modification and Analysis Laboratory (IBMAL) at the University of North Texas contains four ion accelerators with dedicated beamlines for a number of ion beam analysis and modification techniques. The IBMAL currently has a high throughput ion beam focusing system utilizing pairs of Louisiana magnetic quadrupole doublets (LMD) lenses associated with a 3MV single-ended (NEC, 9SH Pelletron) accelerator. The microprobe forming lenses along with annular x-ray detector (four-segment Bruker QUANTAX FlatQuad Silicon drift X-ray detector), and Oxford Microbeams Ltd’s OMDAQ-3 data-acquisition system enables routine microanalysis with ~1 µm spot sizes. Some of the current research work involves µPIXE elemental maps and microanalysis of various biological and environmental samples of rat-brain tissue sections, air-particulates and dust in rainwater collected on filter papers. This presentation will report on some of the interesting results from these studies.

Two works of art, ancient and contemporary, were studied with two Ion Beam Analysis (IBA) techniques, Secondary Ion Mass Spectrometry using MeV primary ions (MeV-SIMS) and Particle-Induced X-ray Emission (PIXE), in order to identify binding materials and pigments used by the artists or in the conservation process. A segment of a conserved painting, dating from the 18th – 19th century, was obtained in the framework of IAEA CRP Project F11021: “Enhancing Nuclear Analytical Techniques to Meet the Needs of Forensic Sciences”. Together with the painting sample, two mock-ups were prepared using lead white pigment mixed with one of the two binders, linseed oil and egg yolk, which are often used in traditional artworks. Samples of three different color regions taken from a contemporary work of art, “SIS 1” by Vjenceslav Richter dating from 1974, were provided from the holdings of the Museum of Contemporary Art, Zagreb, Croatia. Small fragments from the mock-ups and artwork samples were cut and pressed into pure indium for measurement. MeV-SIMS spectra were collected in the positive- and negative-ion modes with 5 MeV Si4+ ion beam, while 2 MeV proton beam was used for the PIXE elemental analysis at the same sample regions. All measurements were performed at the accelerator facility of Ruđer Bošković Institute. The presence of oil-based binding materials was confirmed with MeV-SIMS in the conserved ancient painting sample, as well as in the contemporary work of Vjenceslav Richter, through the detection and identification of fatty acids, and mono- and diacylglycerols. Fatty acid lead soaps, lead oxide species, and other oxidation products were detected with MeV-SIMS in the ancient painting sample. The presence of lead pigment was confirmed with PIXE analysis, and other inorganic pigments were found through the detection of Na, Al, Si, P, S, Cl, K, Ca, Ti, Fe, Zn, As, Rb and Sb. The presence of synthetic organic pigments was confirmed in the contemporary work of art with MeV-SIMS.
Characterising the effect of MeV ion beam irradiation on tissues is significant for optimising proton beam therapy, which is used in cancer treatment. It is also important for optimising protocols for multimodal elemental and molecular imaging. Elemental mapping of trace elements in tissues has been carried out for a long time using nuclear microprobe analysis. However, the effect of MeV ion beams on biological molecules is largely unexplored. Here, we explore whether MeV irradiation of tissue samples causes molecular changes that can be detected using the imaging mass spectrometry techniques matrix assisted laser desorption ionisation (MALDI) and desorption electrospray ionisation (DESI). Homogenates were prepared as described by Swales et al. [1] and mounted on polyethylene (PET), for DESI and HOPG and carbon foil, for MALDI.

Ion beam analysis used a 2.5 MeV H+ beam (~500 pA). Samples were analysed at low (2.48e13 ions/cm2), medium (2.98e14 ions/cm2) and high (5.96e14 ions/cm2) fluences. DESI imaging was subsequently carried out at the National Physical Laboratory. A 95:5 (%v/v) methanol/water spray solvent was delivered at a rate of 2 µl/min and 4 kV capillary voltage. For MALDI experiments, also carried out at NPL, samples were sprayed with CHCA matrix. A Nd:YAG laser (355 nm) was used with a repetition rate of 2000 Hz, a calculated laser energy of 3.6 µJ.

Sequential IBA and MALDI/DESI analysis showed that beam-induced molecular changes were less evident when a MALDI matrix was applied prior to ion beam irradiation (Figure 1). A gradual loss in the intensity of a number of biological compounds could be observed as the fluence delivered to the sample was increased. It was found that the nature of radiation damage was substrate dependent, and we propose molecular changes to biological samples can be mitigated by mounting on a substrate with sufficiently high thermal conductivity. Alternatively, spraying a matrix onto the sample prior to irradiation can be used to mitigate beam damage to organic molecules.
1026-Feasibility of multimodal imaging with ion beam analysis and mass spectrometry imaging techniques

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Elemental and molecular imaging techniques are widely used in biomedical applications for drug delivery studies and disease pathogenesis, with each analysis being carried out independently from one another. This limits the probative value of many investigations, where co-locating elemental and molecular markers are required. This study investigates the feasibility of analysing a single sample using Ion beam analysis (IBA) technique such as PIXE and desorption electrospray ionisation (DESI), a mass spectrometry imaging technique. These includes studies into suitable substrates for DESI and PIXE analysis, as well as the appropriate workflows for multimodal analysis.
Secondary ion mass spectrometry (SIMS) is one of the most commonly used analytical techniques for surfaces of polymers and biological samples, as well as semiconductors and ceramics. Low energy (~keV) ion beams used in conventional SIMS systems are difficult to transport in the ambient. We have developed a SIMS technique that uses swift heavy ion beams (MeV-SIMS) that have a high transmission capability in matter and can be extracted under ambient conditions. We have found that most of secondary ions are generated very near surfaces. Therefore, MeV-SIMS provides a unique opportunity for surface sensitive characterization technique. The MeV-SIMS technique is now being developed in various ion accelerator laboratories in the world and is being established as a new ion beam analysis (IBA) technique.

A specially designed SIMS system was constructed at Kyoto University for ambient SIMS measurements [1, 2]. 6-MeV Cu ion beam is introduced into a target chamber that is kept at ambient conditions. The secondary molecular ions emitted from sample surfaces are extracted through a small orifice into a differentially pumped chamber and measured with an orthogonal acceleration time-of-flight (oa-TOF) mass spectrometer. The electric field is manipulated to suppress chemical noise by adjusting the voltage of the sample and the extraction cone. This system allows measurements of adsorption and desorption of volatile molecules, liquid surfaces and liquid–solid interfaces in the ambient. However, the emission mechanism of large intact molecular ions is still to be clarified and the interpretation of SIMS spectra from liquids is not yet established.

Recent progress on this technique will be presented and discussed along with possible applications for ambient analysis.

1060-ToF SIMS in a Helium Ion Microscope – Elemental mapping on the nm scale

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Helium ion microscopes (HIM) are commonly used as high resolution imaging devices in laboratories all over the world. They deliver superior resolution in the (sub) nanometer range as well as a highest depth of field on conductive and insulating samples. Additionally, the latest generation of HIM devices (Zeiss Orion NanoFab) can be operated with both Helium and Neon ions, and thus offer various opportunities for local surface modifications [1]. Contrast generation in HIM imaging is realized by evaluating the number of secondary electrons (SE). Identification of secondary ions produced by the impacting He+ or Ne+ projectiles was rarely taken into consideration so far, although it provides an additional mechanism for contrast generation. In this contribution, we present the implementation and results of Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) in a HIM. We demonstrate that pulsing the primary ion beam represents an elegant and cost efficient way to integrate SIMS into a HIM without disturbing its excellent imaging capabilities [3]. This technique can be easily retrofitted to existing HIMs [2,3]. Our setup uses a straight secondary ion extraction optics that has been designed and optimized for highest transmission. The high efficiency is the most crucial parameter to collect enough signal from nanoparticles prior to their complete removal by ion sputtering. As a major advantage the time-of-flight approach inherently enables the measurement of all masses in parallel and thus provides the complete picture of the sample composition.

ToF-SIMS represents a versatile add-on that helps the user to access previously unknown details about the sample and is therefore beneficial for many applications. The setup allows to obtain SIMS data (elemental composition) from a certain region of interest or can be used in imaging mode to obtain elemental line profiles and maps of the surface. The beam resolution has been evaluated to 8 nm using the knife edge method, an un-pulsed beam and a 75%/25% criterion. The system has been qualified on test and real life samples from different fields like lithium ion battery research, aerosol analysis, thin film coatings. Selected results will be presented.

Latest attempts on upgrading our system with a delayed secondary ion extraction will be presented as an outlook.

1011-Ion Beam Analysis for the 2020’s An integration of elemental mapping and omics

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Here we present a newly awarded EPSRC Fellowship (EP/R031118/1), which is exploring the synergy between ion beam analysis and mass spectrometry imaging approaches for co-locating proteins, metabolites and trace elements in biological samples at the sub-micron scale.

Our community will be well aware that microbeam IBA has been used for many years in biomedical investigations due to the ability to map trace elements (and, more recently, small molecular fragments) at micron dimensions.

Our team are currently exploring how mass spectrometry imaging tools can be used alongside microbeam IBA imaging. We are exploring two complementary approaches: (a) multimodal mass spectrometry (using laser desorption and electrospray sources) and ion beam trace element imaging; as well as (b) ion beam imaging and molecular profiling. We have developed a new molecular profiling tool, which gives a detailed characterisation of lipids, metabolites and proteins. We will give some initial insights on workflows and how ion beam analysis and mass spectrometry imaging can work in a complementary way.

1050-IonoFLIM – A new imaging modality for nuclear microscopy

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Proton induced fluorescence (PIF) imaging utilizes the spectral fluorescence intensity emitted by a sample excited by the MeV protons for contrast. At CIBA, we have demonstrated PIF imaging in various samples including whole biological cells and several types of fluorescent nanoparticles at resolutions well below the optical diffraction limit of 200 nm [1,2]. Since the energy of the protons (MeV) used in these experiments are far above the UV-visible energies (eV) of the fluorescent probes, there is no selectivity in the excitation of fluorescence and as a result, all components are excited. One type of sample where this poses a problem is biological samples. Biological cells or tissue will naturally emit fluorescence (autofluorescence) under excitation from light (UV, visible) or energetic particles such as electrons and protons. Autofluorescence spectra are typically broad covering the whole visible spectrum [3]. As a result of this broad emission, it is difficult to separate fluorescence that originates from a fluorophore or a probe from the background emission produced by autofluorescence. Unlike the emission spectrum, excited-state lifetime is a property of the fluorophore and its molecular environment. Though the emission wavelengths of typical fluorescent probes widely overlap with autofluorescence, they have distinct lifetimes [4, 5].

Fluorescence lifetime imaging microscopy (FLIM) is an optical technique used to map the spatial distribution of excited-state fluorescence lifetimes within a microscopic sample. Recently, FLIM has been
applied to applications in biology, biomedicine, chemistry, material sciences and many other related fields [6, 7]. In a FLIM experiment, lasers (UV-visible-NIR wavelengths) are used to excite fluorophores or other chromophores with an ultrafast pulse (pico or femtosecond) [6]. The emitted photons are then measured using a fast photodetector and timing electronics in the picosecond range. In this work, the techniques of lifetime measurement using pulsed ion beams and nuclear microscopy will be combined. We have developed the Ion-beam-induced Fluorescence Lifetime Imaging (IonoFLIM) technique for nuclear microscopy, enabling us to separate the fluorescent probes from the background autofluorescence in the time domain with high spatial resolution. First results that demonstrate the power of this new technique will be presented along with the hardware developments and future applications of the technique.


Contributed talks

1019-Beam spot fluctuation due to stray AC magnetic field in Singapore nuclear nanoprobe

Yanxin Dou ¹, Zhaohong Mi ², Jeroen Anton van Kan ², Thomas Osipowicz ²

Nuclear Research and Safety Initiative Singapore-Singapore ¹ National University of Singapore Department of Physics Singapore-Singapore ²

The improvement of the spatial resolution of nuclear nanoprobes is clearly a major common aspiration in the field [1]. However, the major practical limitations stemming from local parameters/conditions in different labs may be dissimilar, resulting in different achievable spatial resolution limits. To our knowledge, the best resolutions (sub 10 nm in the horizontal and about 30 nm in the vertical directions)
were achieved at the Centre for Ion Beam Applications (CIBA) [2]. Our recent research confirmed that beam spot fluctuations due to stray AC magnetic field in our system, limits the spatial resolution in vertical direction. These AC magnetic fields were measured by a magnetic field sensor FLC 100 and an air-cored solenoid, and a simulation model [3] was used to estimate the influence of such stray AC magnetic fields on beam spot fluctuation of our nanoprobe. The results from experiments and simulations, for a range of ion energies, are consistent with the deterioration of the vertical focus size due to AC magnetic fields.


1039-Present status of the tandetron laboratory and the micro and nanobeam lines of ATOMKI

Gyula Nagy ¹, István Rajta ¹, Zoltán Tamás Gaál ¹, István Vajda ¹

Institute for Nuclear Research Tandetron Laboratory Debrecen-Hungary ¹

In 1994, a scanning nuclear microprobe beamline (Oxford Microbeams Ltd.) was installed on the old, home-made Van de Graaff accelerator of Atomki, Debrecen, Hungary. In 2015, a new Tandetron accelerator was purchased from High Voltage Engineering Europe B.V. [1], but the microprobe beamline continued to operate on the old VdG accelerator. In 2018, a new nanobeam endstation (Oxford Microbeams Ltd.) was installed on the new Tandetron accelerator. A first resolution test showed 200 nm spot size for low-current mode and below 600 nm for high-current mode [2]. Shortly after this, several major upgrades were implemented on the Tandetron accelerator, including new ion sources, a large analyzing magnet, etc., resulting in the need of a full re-arrangement of the whole beamline hall. Therefore, the nanobeam line must also be re-installed. By the end of 2019, the old VdG accelerator was shut down permanently, so we started to re-install the microbeam line to the new Tandetron accelerator, too. The presentation summarizes the status of these works. First we introduce the capabilities of the Tandetron accelerator, possible ion species and energy range, stability, brightness, etc. Then, we present the status of the two relevant endstations, the micro- and the nanobeam line, including some technical details (e.g. calculations of possible lens configurations, cooling, vibration, etc.). We describe the most important milestones of the re-installations achieved so far, as well as the future plans, regarding expected beam sizes, planned activities, etc.

1043-Update of the external PIXE beamline at Microanalytical Center of the Jožef Stefan Institute

Kristina Isaković 1, Marko Petrić 2, Zdravko Rupnik 2, Primož Pelicon 2, Mitja Kelemen 3, Matej Vereš 2, Primož Vavpetič 2, Matjaž Kavčič 2

Jožef Stefan International Postgraduate School / Ljubljana-Slovenia 1 Jožef Stefan Institute F2 Department of Low and Medium Energy Physics Ljubljana-Slovenia 2 Jožef Stefan International Postgraduate School, Jožef Stefan Institute F2 Department of Low and Medium Energy Physics Ljubljana-Slovenia 3

In this work the current status of the external PIXE beamline at the J. Stefan Institute is presented. The external PIXE set-up is used to perform measurements in ambient atmosphere on samples which are not suitable for high vacuum conditions. The main goal of current update is to extend the capabilities also towards measurements of elemental distributions in the sample across relatively large surface area (~ 1 cm²) with lateral resolution ~ 100 µm.

For that purpose, the previous set-up has been upgraded by installing magnetic quadrupole lenses (doublet) for beam focussing and replacing the former exit window with thin (500 nm) Si3N4 membrane. In addition, a beam chopper was installed to provide beam dose normalization using the signal of backscattered protons. The results of beam characterization measurements are presented followed by the first examples of measured distribution of different minerals in plant tissue leaves.

1059-Ion microbeams for detector characterization and materials modification with sample heating

Andreo Crnjac 1, Georgios Provatas 1, Mauricio Rodriguez Ramos 1, Marko Brajković 1, Jacopo Forneris 2, Slava Ditalia Tchernij 2, Milko Jakšić 1

Ruđer Bošković Institute Division of Experimental Physics Zagreb-Croatia 1 University of Torino Physics Department Torino-Italy 2

We report about the ongoing development of the ion microprobe end-station at the Zagreb accelerator facility. Recent research interests required the possibility to heat the samples in the microprobe chamber. The heating setup that has been constructed is now able to reach 1000 °C. Customized sample holder prevents heat distribution to nearby elements or breakdown of the high vacuum operation. Up to now, two sets of experiments utilized the heating capabilities: high temperature ion implantation (irradiation) and semiconductor detector characterization. Brief overview of these experiments will be presented. The first application was ion implantation of heavy ions (F, Cl, Fe…) in diamond material at different temperatures, up to 900 °C. This localized implantation helps the exploration of the new color centers in this material. The second application was part of the extensive study of the temperature effects on charge collection properties in diamond detectors [1]. Small areas of the detector were exposed to focused proton beam irradiation to induce defects in the bulk of the material. Ion beam induced charge (IBIC) technique was used to map the electronic properties from damaged areas and pristine (unirradiated) area at elevated temperatures. The data provides insight into the temperature evolution of the radiation
hardness and trapping mechanisms. The effect of the polarization phenomena was also addressed. Finally, we report the new spatial resolution results using heavy ion beams in low current mode (fA). 6 MeV Carbon beam was focused to profile with 140 nm horizontal and 220 nm vertical spot size. Further efforts in the beam resolution refinement are planned to enable new possible applications of the microprobe setup.


**1062-Capillary microprobe for MeV SIMS**

*Klaus-Ulrich Miltenberger*, Max Döbeli, Christof Vockenhuber, Hans-Arno Synal

*ETH Zürich Laboratory of Ion Beam Physics Zürich-Switzerland*

The technique of ion beam collimation with a glass capillary was developed initially as a straightforward and inexpensive alternative to magnetic or electrostatic microprobe lens systems. However the collimation effect, which is completely independent of mass and energy of the primary ion beam, makes the technique ideally suited to produce microbeams of a wide range of very heavy and energetic (cluster) ions for highly efficient IBA techniques like PIXE and MeV-SIMS which only need a primary ion beam of very low intensity [1]. Such a capillary microprobe is employed in the current Capillary Heavy Ion MeV-SIMS (CHIMP) setup at the ETH Zurich 6 MV TANDEM accelerator [2] to collimate a large variety of light and heavy ions with energies up to 80 MeV. Since the high energy part of the beamline is equipped with electrostatic ion optical elements only, the microprobe can be used to provide molecular or cluster primary ion beams (e.g. C60) with large magnetic rigidity to study the desorption process in MeV-SIMS. Capillaries with outlet diameters down to a few µm have been used in combination with a piezo sample stage to achieve secondary ion imaging with micrometer resolution [3].

The setup and its performance will be presented and the potential of capillary microprobes for mass spectrometric imaging will be discussed.

1001-Electronic energy loss of heavy ions at low energy in LR 115 Kapton SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} Monte Carlo simulation and LSS Modified theory

Jaouad El Asri \textsuperscript{1}, Omar El Bounagui \textsuperscript{1}, Najim Tahiri \textsuperscript{1}, Hassane Erramli \textsuperscript{2}, Abdelouhed Chetaine \textsuperscript{1}

FSR Physics Rabat-Morocco \textsuperscript{1} FSSM Physics Marrakech-Morocco \textsuperscript{2}

The electronic stopping power and energy loss of LR-115, Kapton, SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} polymeric foils has been calculated, using Monte Carlo and LSS modified theory, for Z = 4Be, 5B, 6C, 7N and 8O ions covering the energy range ~ 0.1–0.1 MeV/nucleon. These calculated electronic stopping power values have been compared with the corresponding values obtained by SRIM, CasP and MSTAR codes. In addition, the results obtained by our calculations for SiO\textsubscript{2} and Al2O\textsubscript{3} are compared with experimental results, we found that, are in close agreement.

1004-Effect of swift heavy ion irradiation and annealing on the microstructure of implanted SiC

Hesham Abdelbagi \textsuperscript{1}, V.A. Skuratov \textsuperscript{2}, S.V. Motloung \textsuperscript{3}, E.G. Njoroge \textsuperscript{4}, M. Mlambo \textsuperscript{4}, J.H. O’Connell \textsuperscript{4}, J.B. Malherbe \textsuperscript{4}, T.T. Hlatshwayo \textsuperscript{4}

Shendi University Physics Department Shendi-Sudan \textsuperscript{1} Joint Institute for Nuclear Research Physics department Dubna-Russia \textsuperscript{2} Nelson Mandela Metropolitan University Physics department Port Elizabeth -South Africa \textsuperscript{3} University of Pretoria Physics Department Pretoria-South Africa \textsuperscript{4}

The influence of swift heavy ion (SHI) irradiation on the microstructure of polycrystalline SiC individually implanted with silver (Ag) and strontium (Sr) were investigated using Raman spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM) and Rutherford backscattering spectrometry (RBS). 360 keV silver (Ag) and strontium (Sr) ions were implanted separately into SiC at room temperature (RT) all to a fluence of 2x1016 cm\textsuperscript{-2}. Some of the implanted samples were irradiated with Xe ions of 167 MeV (SHI) to a fluence of 3.4x1014 cm\textsuperscript{-2} and 8.4x1014 cm\textsuperscript{-2}, all at RT. The as-implanted and SHI irradiated samples were vacuum annealed from 1100 to 1500 oC in steps of 100 oC for 5 hours. Implantation of silver (Ag) and strontium (Sr) amorphized the SiC, while SHIs irradiation of the as-implanted SiC resulted in limited recrystallization of the initially amorphized SiC. Annealing at 1100 °C caused more recrystallization on the un-irradiated but implanted samples compared to SHI irradiated samples. This poor recrystallization of the irradiated SiC samples was due to the amount of impurities (i.e. concentration of Ag or Sr atoms) retained after annealing at 1100 °C. Raman and SEM results showed that annealing of the un-irradiated but implanted samples at 1100 °C resulted in large average crystal size compared to the irradiated samples annealed in the same conditions. At 1500 °C, a carbon layer appeared on the surface of the irradiated and un-irradiated but implanted with Ag and Sr samples. This was due to the decomposition of the SiC and subsequent sublimation of silicon leaving a free carbon layer on the surface.
1034-Microbeam analysis of topographic microstructures shadow effects in ion beam analysis

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Ion beam analysis is readily used to quantify the elemental composition of a diverse range of samples assumed to consist of uniform planar layers. Yet, there is an emerging interest in the analysis of high aspect ratio topographic microstructures. Microbeam ion beam analysis involving a variety of scattering geometries should be able to yield the required 3D information on the sample composition. However, the technique has not yet been fully explored nor documented. In this work, we demonstrate that the composition of topographic microstructures can be determined by using microbeam Rutherford backscattering and particle induced X-ray experiments, provided that the effects of shadowing due to the sample topography are considered.

Micrometre sized structures are among others applied in microfluidics, for which it is important to have a precise control over the hydrophobic or hydrophilic nature of the surface in different steps of the fabrication process. A method to probe the functional nature of the surface is by applying a single pulse of atomic layer deposition with a heavy element, and by consecutively quantifying the deposited material using ion beam analysis techniques. The detected signal is, however, strongly affected by the shadowing of backscattered ions and particle induced X-rays during a microbeam experiment on high aspect ratio structures at the microscale. We develop a framework to identify the probed volumes necessary to reconstruct a 3D model of the structures and demonstrate the methodology on trench and pillar like microfluidic test structures. The samples underwent one cycle of atomic layer deposition using a hafnium precursor. Subsequent microbeam Rutherford backscattering and particle induced X-ray experiments, when considering the shadowing effects, allow us to determine the areal density of hafnium on the various surfaces of the structures and thus to determine the respective functional properties.
In 2020, the nuclear microprobe at Jožef Stefan Institute has been a subject of several instrumental upgrades. New digital acquisition system has been commissioned by Oxford Microbeams Ltd. and is controlled by the OMDAQ-3 program. The acquisition system comprises of six independent acquisition channels with analog ADC units, as well as a high resolution Core TDC unit for Time-Of-Flight (TOF) MeV-SIMS imaging mass spectroscopy. In addition, the continuous-discharge resistive feedback preamplifiers are read by a two-channel CAEN digital pulse processor. All these channels are available for the live and list-mode streams in the various mapping modes, enabling the scanning frames consisting of up to 4096 x 4096 pixels. A new Silicon Drift Detector (SDD) with 8 µm Be window for quantitative PIXE with low-energy X-rays starting from 0.7 keV has been installed as a replacement to the earlier X-ray SDD, which was irreversibly radiation-damaged after a decade of operation without blocking the backscattered primary ions. To enable micro-PIXE with extreme solid angle, a new four-segmented SDD with annular geometry is being assembled by PNDetector, and is to be commissioned at the microprobe in September 2020. The sensors are protected by 125 µm thick Be window in order to block backscattered protons during micro-PIXE with 3 MeV-protons and will cover the solid angle of up to 1 strd. The existing TOF mass spectrometer for MeV-SIMS is under upgrade with a reflectron-stage, enabling two modes of operation: linear 2 meter long TOF with an MCP stop detector, and reflectron operation with Electron Multiplier Detector with Conversion Dynode, providing 10 kV post acceleration for improved detection efficiency for very heavy secondary molecular ions with masses exceeding 1 kDa.
Einstein’s revolution: Quantum technology for the 21st century quantum computer

David Jamieson 1

University of Melbourne, Melbourne, Australia 1

Einstein’s most revolutionary idea, of the light quantum, has led to the concept for a radical new type of computer that uses the strange rules of quantum mechanics to process information encoded in quantum bits, qubits. Especially promising qubits are ion implanted donor atoms in isotopically pure semiconductors including silicon. Successful development of large-scale devices that can solve important problems that cannot be solved by classical machines requires overcoming formidable scientific and technical obstacles. We will need to manipulate and interrogate single atoms with unprecedented precision. This presentation looks at the emergence of quantum technology, our group’s work engineering quantum states into single atoms implanted in silicon and how we plan to build the first quantum machines.
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Figure 2: Rise time histogram
Figure 3: Resolution at increasing OCR
Figure 4: MnKα Spectra at varying OCR
Figure 5: Quantum Efficiency curve of SDD sensors
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