Vacuum Technology Division
Room 301 - Session VT-MoM

Vacuum Measurement and Gas Analysis and Vacuum Technology for Quantum Applications

Moderator: James Fedchak, National Institute of Standards and Technology

8:20am **VT-MoM-1 "Much to Do About Nothing:" Advancing Compact UHV Packages for a "Quantum Everywhere" Future**, ***Alex Tingle,*** ColdQuanta **INVITED**

The burgeoning quantum industry demands scientific and engineering innovation at a breakneck rate. Beyond invention and supply chain challenges of current and near-term laboratory-scale quantum systems, the not-so-distant future of compact, field-deployable, quantum products (such as computers, clocks, inertial sensors) will require cost-effective and mass-producible packages. Cold atom quantum technology is well-positioned to serve a wide variety of quantum applications, and advances in vacuum technology are enabling this cold atom quantum future. ColdQuanta strives to support the quantum ecosystem and cultivate a technology base that serves many emerging applications with a common underpinning technology, namely a compact cold atom UHV package: the Quantum Core. Advancing the Quantum Core will pave the way to diverse quantum products at scale. We will overview vacuum technology's crucial role in the quantum industry, dive into some specific technologies, and gaze into the future of commercialized Quantum Cores powering quantum products in diverse applications.

9:00am **VT-MoM-3 Non-Magnetic UHV Chambers and Feedthroughs for Quantum Applications: A Challenge for Vacuum, Optics and Mechanics**, ***Klaus Bergner**, J. Hertel, A. Trützschler, M. Flaemmich,* VACOM Vakuum Komponenten & Messtechnik GmbH, Germany

Quantum technology is currently experiencing a huge push towards commercialization. This means that basic experiments are more and more transferred into industrial applications. This means that enabling technologies must meet new quality criteria. In particular, the interplay between vacuum technology, mechanical and optical requirements must be taken into account. Vacua in the UHV/XHV range have to be achieved and several optical access ports for different optical tools have to be positioned in the range of a few µm to each other and.

In order to fulfill all this demands efficiently, aluminum CF components offer the possibility of providing customized solutions with high geometrical accuracy, reduced weight, outgassing rates of 1E–14 mbar*l/s/cm² as well as non-magnetic properties.

The talk covers the design of non-monolithic and monolithic CF vacuum chambers made from aluminum by using AluVaC®-technology. By discussing customized chamber designs, the talk shows that a monolithic design leads to a paradigm shift, since a monolithic chamber can be designed much more compactly, manufactured faster and without welding seams.

In combination with different optical components, the talk addresses the UHV compatibility of AluVaC®-viewports as well as VACOM made optical feedthroughs. Thorough different tests prove the UHV suitability with low outgassing rates shine light on product-relevant changes under extreme conditions.

9:20am **VT-MoM-4 Comparison of Quantum and Classical Vacuum Standards**, ***Daniel Barker**, N. Klimov, E. Tiesinga, J. Fedchak, J. Scherschligt, S. Eckel,* National Institute of Standards and Technology

We present a comparison of NIST's cold atom primary vacuum standard and a dynamic expansion vacuum standard. The cold atom vacuum standard (CAVS) converts the background-gas-induced loss rate of atoms from a magnetic trap into vacuum pressure using atom-molecule collision cross-sections calculated from first-principles quantum scattering theory. An extreme-high-vacuum (XHV) flowmeter and dynamic expansion system generate low-uncertainty partial pressures within the CAVS atom trap. To validate the CAVS, we compare its measured pressure to the pressure set by the dynamic expansion vacuum standard. We will present comparisons using a variety of noble gases and common vacuum contaminant species colliding with two species of sensor atoms. Our results open the way to vacuum gauge calibrations in the XHV and deployable pressure sensors with embedded traceability.

9:40am **VT-MoM-5 Direct Comparison of Two Portable Cold Atom Vacuum Standards**, ***Stephen Eckel,*** National Institute of Standards and Technology (NIST)*; L. Ehinger,* Seattle University*; D. Barker, J. Fedchak, J. Scherschligt,* National Institute of Standards and Technology (NIST)

We demonstrate the operation of the portable cold atom vacuum standard (pCAVS) by directly measuring the same vacuum with two independent devices. The pCAVS, designed as a replacement to the Bayard-Alpert ionization gauge, measures the loss rate of atoms from a magnetic trap, and converts that loss rate into a vacuum pressure using *ab initio* quantum-scattering calculations. Our pCAVS devices share the same laser system. Loss rate measurements are interlaced between the two, allowing for simultaneous readout. When initially assembled, the two pCAVS together detected a leak on the order of 10^{-6} Pa L/s. After fixing the leak, the two pCAVS measured the same pressure of 41.8 nPa with approximately 2 % uncertainty. Operation of the pCAVS was found to cause some additional outgassing in the vacuum, raising the base pressure approximately 1 nPa. With improved thermal management and better modeling of other loss mechanisms, we expect that the uncertainty can be decreased sufficiently to allow primary pressure measurements in the extreme-high-vacuum range (< 10^{-9} Pa).

10:00am **VT-MoM-6 Reference Ionization Vacuum Gauge**, ***Martin Wüest**, F. Scuderi,* INFICON Ltd., Liechtenstein*; J. Šetina,* Institute of Metals and Technology, Slovenia*; K. Jousten, M. Bernien,* Physikalisch-Technische Bundesanstalt - Berlin, Germany*; C. Illgen,* Physikalisch-Technische Bundesanstalt - Berlin, Germany*; N. Bundaleski,* Nova School of Sciences and Technology, CEFITEC, Portugal*; B. Jenninger, A. Stöltzel,* CERN, Switzerland

In the framework of the EURAMET project 16NRM05 a novel ionization gauge was developed. The goal was to develop a stable gauge suitable as a reference standard in the high vacuum range. A robust design eliminates many of the weak points of present day Bayard-Alpert gauges. Results of performed measurements show sensitivity spread within an interval ± 1.5 % at 95 % confidence level. Due to its simple geometry, sensitivity values can in principle be computed for any gas with a known ionization cross section. Known and stable relative sensitivity factors are important properties for the calibration of mass spectrometers. We will present some aspects of the gauge design and performance in conjunction with an associated controller.

10:40am **VT-MoM-8 Towards an Ionization Vacuum Gauge Suitable as a Reference Standard**, ***Nenad Bundaleski,*** CEFITEC, NOVA School of Science and Technology (FCT-NOVA), NOVA University Lisbon, Portugal **INVITED**

Ionisation vacuum gauges are the only pressure measurement devices covering a pressure range from high vacuum down to extremely high vacuum. However, these instruments lack precision, accuracy and stability, which is a misfortunate fact knowing the importance of these pressure ranges in both science and high technologies. Calibration of mass spectrometers and measurement of pumping speeds are examples of tasks that are particularly vulnerable in that respect. There are two major sources of problems with the operation of ionisation gauges: maintaining stable path lengths of primary electrons throughout the ionisation volume, and contribution of secondary particles emitted from electrodes (photons, electrons, ions and neutrals) to the pressure reading. These phenomena will be analysed in some detail in the frame of this talk, including the solutions applied in different available gauges to handle them. In the second part of the talk, we will present a design of a novel ionisation gauge recently developed for metrology applications in high vacuum, and discuss solutions aiming to suppress the above mentioned issues. However, the proposed design may potentially have problems with space charge effects, which limits its range of operation at the lowest pressures.

11:20am **VT-MoM-10 Evaluating low Pressure Resolution Limits for Optical Refractometry**, ***Jacob Ricker**, K. Douglass, J. Hendricks,* National Institute of Standards and Technology (NIST)*; S. White, S. Syssoev,* MKS Instruments, Inc.

NIST with a collaboration research and development partnership with MKS Instruments has created a portable Fixed Length Optical Cavity (FLOC) pressure standard based on gas refractivity. The NIST team is now working to push the limits of pressure measurement into the UHV range. The goal for the new device would be to fill the gap in quantum-based traceability that currently exists between the FLOC and the Cold Atom Vacuum Standard, from 1 Pa to 10^{-5} Pa. To achieve the measurement goals, several sources of noise and drift need to be studied and eliminated. The desired sensitivity requires a frequency measurement (heterodyne signal between two 194 THz cavities) to have noise on the order of 1 Hz. To achieve this, the portable FLOC must be redesigned with state-of-the-art lasers and cavity mirrors, vibration isolation, and improved thermal control. The current FLOC low pressure performance will be estimated and initial testing results along with our proposed pathway to ultra-high vacuum measurements will be presented.

11:40am **VT-MoM-11 Vacuum Fixed Length Optical Cavity (VFLOC): Optical Pressure Measurements Approaching Ultra-High Vacuum*, Kevin Douglass,*** *J. Ricker, J. Hendricks,* NIST

With the goals of achieving quantum traceability over a broad pressure scale NIST is developing a Vacuum Fixed Length Optical Cavity (VFLOC) that will have a base pressure in the ultra-high vacuum range.The current FLOC operates in the 1 kPa to 150 kPa pressure range and the Cold Atom Vacuum Standard (CAVS) has an upper limit near 10^{-5} Pa.The main limitation for pressure resolution and ultimate base pressure is the fractional frequency stability or frequency noise of dual cavity heterodyne signal.For operation at 1542 nm, hertz level frequency noise is required for achieving pressure noise floor on the order of 10^{-6} Pa (10^{-8} Torr).We will discuss current system status, design and recent results.

Vacuum Technology Division
Room 301 - Session VT-MoA

Vacuum Technology for Accelerators

Moderators: Giulia Lanza, SLAC National Accelerator Laboratory, **Yevgeniy Lushtak**, SAES Getters USA

1:40pm **VT-MoA-1 Developments of the Vacuum Systems Required for the Electron Ion Collider***, **Charles Hetzel**,* Brookhaven National Laboratory **INVITED**

The Electron-Ion Collider (EIC) is a new particle accelerator which collides electrons (10 GeV, 2.5A) with protons (275 GeV, 1.0A) and nuclei that will be constructed at Brookhaven National Laboratory in the coming decade. This new machine will utilize the most of the existing infrastructure and accelerator complex of the currently operating Relativistic Heavy Ion Collider (RHIC). The hadron storage ring (HSR) will reuse some of the two superconducting RHIC storage rings. An electron storage ring (ESR) will be installed in the existing RHIC tunnel to provide electrons for beam collisions with the HSR hadron beam in up to two interaction regions. Fully polarized electron bunches will be injected to the ESR at fully energy (up to 18GeV) by a rapid-cycling synchrotron (RCS) which will also be constructed in the same accelerator tunnel. In order for this complex to reach its fully envisioned potential (luminosity of 10^{34} $cm^{-2}s^{-1}$), many new and challenging vacuum systems, including more than 8km of new UHV beam pipes as well as many upgrades to the existing storage rings will be required. During this presentation, I will be providing a brief overview of the various vacuum systems as well as some of the many challenges which need to be overcome.

2:20pm **VT-MoA-3 Vacuum System of the MAX IV 3 GeV Storage Ring: Design and Performance***, **Marek Grabski**, M. Grabski,* Max IV Laboratory, Sweden **INVITED**

MAX IV 3 GeV storage ring is the first synchrotron light source implementing compact multi-bend achromat (MBA) magnet lattice and vacuum system fully coated with non-evaporable getter (NEG). The storage ring is in operation for over 6 years, providing ultra-low electron beam emittance and delivering photon beams to beamlines from insertion devices.

The storage ring vacuum system, based on the NEG coating, proved to be reliable and has very good performance. The total average pressure is below 1e-9 mbar and is reducing with the accumulated beam dose since the start of the operation. The total electron beam lifetime of approximately 5 Ah is not limited by the vacuum related beam lifetime which is greater than 39 Ah.

Several successful installations were accomplished on the storage ring during shutdowns. Some interventions were performed utilizing purified Neon venting to avoid re-activating of the NEG film, thus saving installation time without compromising the accelerator performance.

Design principles, performance and operational status of the 3 GeV storage ring vacuum system will be presented.

3:00pm **VT-MoA-5 Fabrication and Assembly Status of the APS-Upgrade Storage Ring Vacuum System***, **Jason Carter**, O. Mulvany, G. Wiemerslage,* Argonne National Laboratory

The Advanced Photon Source Upgrade (APS-U) project is progressing towards the coming dark time for APS and installation and commissioning of the new storage ring including a new vacuum system. Vacuum system design is complete and procurements and vacuum chamber production is underway for over 2400 vacuum chambers, absorbers, and beam position monitors as well as supplemental hardware. A pre-assembly phase of vacuum system and magnet modules has begun in the summer of 2022. A total of 200 modules, 5 each per 40 sectors, will be installed in the APS-U storage ring. This presentation will fabrication status of the various vacuum components, the status of vacuum system assembly, and the challenges ahead. Challenges include installation within restricted space access, preventing UHV contamination, achieving precision alignment goals, and protecting sensitive components such as thin-walled vacuum chambers, bellows, and delicate RF liners while maintaining progress in a heavy-duty assembly area.

4:00pm **VT-MoA-8 CW Superconducting Linac for the LCLS-II HE Free Electron Laser at SLAC***, **Marc Ross**,* SLAC National Accelerator Laboratory **INVITED**

This year the X-ray Free Electron Laser 'LCLSII', will start commissioning activities. LCLS-II (Linac Coherent Light Source - II) is a photon science user facility that produces ultra-short very high peak-power narrow-band X-ray pulses, up to a million pulses per second and up to 5 keV photon energy. The facility is used primarily for applied science, including for example molecular biology, matter in extreme conditions, and engineered materials. The high repetition rate and ultra-short pulses will allow scientists to make stop-action movies at atomic scales.

The heart of the facility is a new CW 4 GeV superconducting electron linac based on the well-developed 1.3 GHz TESLA technology. The linac consists of 37 Cryomodule units that house 296 nine-cell niobium cavities operating submerged in superfluid liquid helium at 2 Kelvin. A major advancement is the monolithic nature of the linac with the cryomodules directly connected to each other to make a ~ 100 meters long cryogenic volume. It is believed this advancement helps keep contaminants such as particulates and organic chemicals away from the RF cavity vacuum volume, and it is acknowledged Cryomodule exchange is more difficult. No getters or ion pumps are used in the long cryomodule string.

This is the first superconducting linac to be constructed using niobium cavities that have their surface doped with nitrogen. This recent innovation makes the superconductor 3 to 4 times less resistive and allows the entire facility to fit within the capacity of a single liquid helium cryoplant. The doping is carried out by the cavity vendors at the end of the high temperature degas vacuum bake. The doped cavity production run ended in 2019 with excellent performance results.

Assembling the cryomodules and integrating them in the accelerator enclosure tunnel requires the best available particulate and contamination control. It is believed that a single ~micron sized particle or contamination-spot near the high voltage iris of the accelerator cavity will substantially degrade its voltage performance. Following pioneering work at the Oak Ridge Spallation Neutron Source, we plan to deploy a chemically-active plasma processing technique.

In 2020 SLAC and its partners, Fermilab and Jefferson Lab, embarked on an upgrade project called LCLS-II-HE to extend the capability of the linac from 4 to 8 GeV. The upgraded linac will be 1 km long and will be complete in 2027. In this presentation we will show the application of accelerator technology to the ultra-high performance LCLS-II-HE CW superconducting linac.

4:40pm **VT-MoA-10 Upgrades for the Jefferson Lab Injector and Linac Accelerator Vacuum Systems***, **Marcy Stutzman**,* Thomas Jefferson National Accelerator Facility

The accelerator vacuum systems at Thomas Jefferson National Accelerator Facility (Jefferson Lab) were initially designed in the 1980s. Over the past several years, the injector beamline vacuum has been upgraded during the first phase of the injector upgrade, and more improvements are planned for the upcoming phase 2 work. Enhanced pumping has also been implemented in the warm girders between the accelerator cryomodules as they are refurbished and replaced in the linacs. I will describe the competing factors for the accelerator vacuum, including the implementation of improved pumping and materials processing for the injector upgrade and quantify the operational results of the enhanced vacuum system. Additionally, I'll describe the goals of the upgrades to the warm girders in the linacs, and compare performance between the zones with added NEG pumping compared to the legacy zones.

5:00pm **VT-MoA-11 Vacuum Leak Detection with Variational Smoothing for Vacuum Process Chamber***, **Taekyung Ha**,* PSK, Republic of Korea

Fault detection is an important method in semiconductor manufacturing for monitoring equipment condition and examine the potential causes of the fault. The vacuum leakage is considered one of major fault in semiconductor processing. Unnecessary O_2, N_2 mixture, major components of atmosphere, creates unexpected process results hence drops yield. Currently available vacuum leak detection systems in vacuum industry are based on helium-mass spectrometers. It is used for detecting the vacuum leakage at sole isolation condition where chamber is fully pumped, but unable to use at in-situ detection condition that while process is on-going in the chamber. In this study, a chamber vacuum leak detection method named variational smoothing autoencoder has been presented, utilizing common data which gathered during normal chamber operation. This method was developed by analyzing a simple list of data, such as temperature of the chamber body and the position of auto pressure control (APC) to detect any change of leakages in the vacuum chamber.

The weakest point of data smoothing is the loss of information. To improve this problem, a variational smoothing method was developed. The length of the process log data is slightly different for each process due to the limit of command processing according to the sequence of the computer. To improve this problem, we partition the time series data and extract the segment information. The extracted segment information is strongly related. So, the autoencoder model was applied to train well on highly relevant data. The proposed method, variational smoothing autoencoder model, showed the best performance, area under the ROC curve (AUC) by 0.84 and accuracy by 0.76. Variational smoothing autoencoder were effective in classifying abnormalities by predicting time series data of semiconductor facility sensors.

Vacuum Technology Division
Room 301 - Session VT-TuM

Vacuum Technology for Large Vacuum Systems

Moderators: Chandra Romel, Consultant, **Marcy Stutzman**, Jefferson Lab

8:00am **VT-TuM-1 Vacuum Materials for the Next Generation Gravitational Wave Detectors***, **Ivo Wevers**, G. Bregliozzi, P. Chiggiato, M. Rimoldi, C. Scarcia, M. Taborelli,* CERN, Switzerland **INVITED**

Gravitational waves were detected for the first time in 2015 by the LIGO which, since then, has measured several other events in conjunction with VIRGO. These achievements have stimulated studies for next-generation gravitational telescopes to enlarge the discovery potential of such scientific facilities. Two studies are presently considered: the Cosmic Explorer (CE) and the Einstein Telescope (ET) in USA and Europe, respectively. To increase the detection performance a key parameter is the length of the Fabry-Perrot cavities in which high power laser beams are stored in an ultrahigh vacuum. For both CE and ET, more than 100 km of ~ Ø 1 m vacuum pipes are required, which would represent up to 50% of the total budget of the new experimental facilities if the LIGO and VIRGO's configurations were adopted. To reduce the cost impact of the vacuum system, unconventional materials, less expensive pipe manufacturing and different surface treatments are scrutinized. In this work, we present measurements performed on low carbon steel (mild steel), having been proposed as an alternative to stainless steel. The outgassing rates of several as-cleaned low carbon steels were measured. Specific hydrogen outgassing rates at room temperature in the 10^{-15} mbar l s^{-1} cm^{-2} were measured for bakeout temperatures as low as 80°C for 48 hours. Water vapour outgassing rates of unbaked samples were similar to or higher than those of stainless steel. To reduce water vapour outgassing, so that a bakeout can be avoided, a silicon coating was proposed. The coating has been produced by chemical vapour deposition with silane as precursor gas; the resulting layer was several hundreds of nanometres thick and resulted in the reduction of the water vapour outgassing rate by a factor 10. Such a value is not low enough to eliminate the need of a bakeout but could open the possibility of temperature treatments below 100°C. Room-temperature specific hydrogen outgassing rates of the Si coated steels in the low 10^{-14} mbar l s^{-1} cm^{-2} were measured after bake-out at 80°C for 48 hours. The hydrogen intake in the studied steels during the coating was investigated by thermal desorption spectroscopy. Optimisation of the mild steel is under study in collaboration with industry to improve vacuum performance and corrosion resistance.

8:40am **VT-TuM-3 Vacuum Design for a Cryogenic Gravitational Wave Detector***, **Rana Adhikari**, C. Wipf,* California Institute of Technology **INVITED**

In 2016, the Laser Interferometer Gravitational-wave Observatory (LIGO) collaboration announced the first detection of gravitational waves (GWs) from the merger of black holes. These ripples in the fabric of spacetime are measured on the earth by laser interferometry. In order for these instruments to work, they must be able to measure mirror motions at the level of 10^{-21} m (100 billion times smaller than a hydrogen atom). The next generation of these instruments will be operated at cryogenic temperatures and use squeezed light to reduce the quantum measurement uncertainty. In this talk I will describe the limits to ultra-precision measurement and how the design of the vacuum system, cryogenic temperature, surface treatments, and laser wavelength affect the measurement. A successful vacuum design would enable the detection of exotic astrophysical phenomena from across the entire universe.

9:20am **VT-TuM-5 CSI; the New Space Calibration Facility at TNO***, **Freek Molkenboer**, R. Jansen,* TNO Science and Industry, the Netherlands*; W. van Werkhoven, T. Luijkx, W. Mulckhuyse,* tno Science and Industry, the Netherlands

In early 2018 TNO started with the conceptual design of a new Space calibration facility, called CSI. The CSI facility will be used for the performance verification and calibration of optical Earth observation instruments on satellites. before the summer of 2022 the facility will be installed and commissioned, and in Q4 2022 ready to receive customers. CSI consists of a few major subsystems, a Thermal Vacuum Chamber (TVC), an instrument manipulation system (consisting of a hexapod and rotation table), a set of optical stimuli and an overall control system.

The TVC will be a vertically positioned stainless steel cylinder with a diameter of 2.75 meters and a height of 2.5 meters. The chamber and thermal shrouds are designed with a diagonal entry, resulting in a wedge-shaped bottom half and top half. This reduces the total height required for opening and operating the chamber as well as facilitating easy loading of the space instrument.

The thermal shroud of the TVC will be able to create an environment between 193K and 353K Two thermal plates will be present to cool areas of the instrument down to 100K if required. The vacuum system consists of two turbomolecular pumps and two cryopumps to reach the ultimate pressure of at least 10e-7 mbar. The vacuum conditions and composition of residual gasses in the TVC will be monitored with an RGA (Residual Gas Analyser) and a QCM (Quarts Crystal Microbalance).

During the calibration of a Space instrument, its orientation relative to the calibration light sources (Optical Ground Support Equipment or OGSE) has to be changed with extremely high accuracy and reproducibility. To achieve this, TNO has selected a vacuum compatible hexapod on a rotation table that meets the stringent accuracy and stability requirements of such an operation. In order to achieve these extreme stability requirements - both in the order of 0.001 degrees - TNO has designed an active thermal system around the hexapod to locally create a thermally stable environment.

During this talk I will discuss the performance of TVC and the instrument manipulation system

9:40am **VT-TuM-6 The Challenges of Heating a Sample in Vacuum***, H. Bekman, **Johannes Velthuis**, F. Molkenboer,* TNO Science and Industry, the Netherlands

Heating a sample up to 400°C in a vacuum system seems not to be complicated, however when this same sample must travel through several vacuum chambers / load locks before arriving at its test location it becomes a greater challenge.

To overcome this stated challenge that is present at EBL2, a large Extreme Ultra-Violet Lithography (EUVL) test facility at TNO that used for EUVL lifetime experiments, we are in the process of designing a special sample holder that can reach, and control the sample temperature between ambient and 400°C.

The sample holder is being developed as part of the EU program, ID2PPAC. The objective of the project is to investigate EUV-material interaction effects at elevated temperatures. This research will contribute applicable knowledge that will result to better material selection in EUVL applications.

It is expected that the last version of the sample holder will require some logic control elements in the sample holder, this because of the limited pinout (number of electrical connections) of the sample holder. The development and testing sub-assemblies of this last version will be time consuming task because a lot of boundary conditions need to be tested.

To ensure that testing of materials can be tested at an earlier phase than before the completion of the last version of the sample holder, two forerunners will be first designed and manufactured.

A complication originates from the EUV power hitting the sample. This EUV power is a heat source that heats up the sample under test. One version will use a low power heater element to control the temperature, this one however is limited in the amount of EUV power the sample can receive, this to prevent overheating the sample.

The second sample holder will be used when the EUV radiation is higher. The sample holder will control the sample temperature by adjusting the backfill pressure between the sample and a colder temperature-controlled element.

By controlling the backfill pressure, the thermal conductance between the sample and the colder temperature-controlled element will change, this method will enable us to cool, and control the temperature of the sample.

During this presentation we will discuss the need for this sample holder, the design, and results of the two first versions of the sample holder. We expect also to be able to present the final design of the last version of the sample holder.

11:00am **VT-TuM-10 Design of ITER Roughing Pump System***, **Charles Smith**, S. Smith,* US ITER **INVITED**

US ITER is charged with supplying mechanical and cryogenic vacuum roughing components to the ITER Organization as part of the United States' commitment to the ITER Project. The Rough Pump system (RPS) as it is known, connects to the Cryostat vacuum vessel (vacuum volume 8500m^3), Torus vacuum vessel (vacuum volume 1400m^3), Neutral beam injector ports, Type 2 Diagnostic instrumentation, and the Service Vacuum System. The RPS provides support for the roughing of these volumes, backing to localized high vacuum pumping stations, and regeneration of the Torus and Cryostat cryopumps. Due to the nature of the ITER machine, traditional gasses (nitrogen, air, helium, etc.) are pumped along with hydrogen isotopes (H_2, D_2, T_2, and combinations thereof). Therefore, the RPS system has specialized roughing trains dedicated to handling each application.

The Non-Active Roughing Systems, defined as systems in which tritium is not expected to be present, employ traditional commercially available pumping technologies. The Non-Active pumping system supports the Cryostat volume roughing, Cryostat Cryopump regeneration, and the Non-Active portion of the service vacuum system. The Active Roughing Systems, defined as systems in which at least some level of tritium is expected to be present, employ all-metal seal roughing pumps coupled with cryogenic systems in the process flow. These all-metal seal pumps are being specifically designed for this application. The cryogenic systems are located in the process stream between the ITER machine vacuum volumes and the active mechanical roughing pumps in order to capture both the hydrogen isotopes and water vapor prior to entering the mechanical pump skids. The cryogenic systems consist of Cryogenic Viscous-Flow Compressors (CVCs) and Condensable Vapor Devices (CVDs). Supercritical and gaseous Helium are supplied from the centralized cryogenic plant and distributed to the RPS systems via Cryogenic Transfer Lines (CTLs) connected to three Cryogenic Distribution Boxes (CDBs) which distribute the cryogens to the CVCs and CVDs using cryogenic jumper connections.

This talk will discuss the unique aspects of the design and requirements of the RPS mechanical and cryogenic pumping elements which allow ITER to engage in the critical science of developing sustainable burning plasma operations to facilitate the design and construction of commercial fusion power plants.

11:40am **VT-TuM-12 Monte Carlo Simulation Studies to Support an Integrated Design for the Cryogenic Vacuum Systems of the Einstein Telescope***, **Xueli Luo**,* Karlsruhe Institute of Technology, Institute for Technical Physics, Germany*; S. Hanke, K. Battes, C. Day,* Karlsruhe Institute of Technology (KIT), Germany

Europe is going to develop a third-generation underground gravitational wave (GW) observatory, known as the Einstein Telescope (ET). It is designed as a novel equilateral triangle with 10 km long arms and the detectors in each corner. Any two adjacent arms compose two independent interferometers. One interferometer will detect low-frequency gravitational wave signals (LF), while the other will be optimized for operation at higher frequencies.

In order to reduce seismic noise, thermal noise and other systematic noise, the whole system will be 200 to 300 m underneath the ground; the beamline pipes, the suspension towers and the cryostat containing the mirror require ultra-high or high vacuum conditions; and the main optics will partly be cooled to cryogenic temperatures below 20 K. In this way, the GW detecting sensitivity of ET will be significantly increased compared to the current advanced detectors (Virgo, LIGO) and the frequency band will be expanded to lower frequencies. The integral ET vacuum system comprises three different parts: (i) the beamline vacuum characterised by outgassing from the pipe walls, (ii) the tower vacuum characterised by outgassing from the suspension arrangement, and (iii) the cryogenic vacuum systems around the LF mirror.

In this paper, a Test Particle Monte Carlo model has been established with the KIT in-house code ProVac3D, to allow for a system analysis of the cryogenic vacuum area. It assesses the impinging rate of residual gas on the cryogenic mirror, depending on the particle sources from the beamline pipes and from the tower, which are systematically varied. With that, the expected speed of frost formation is estimated, which is critical due to degradations of the optical performance, and helpful information on engineering limits are derived. These simulation results are useful to find how far the cryopump section will influence the condition in the warm beamline pipe and the gas flow rate to the optical mirror. As a second major contribution, a shielding concept around the mirror is presented which reduces the gas load to a level fulfilling the requirements.

Vacuum Technology Division
Room 301 - Session VT-TuA

Vacuum Pumping, Leak Detection, and Modeling

Moderators: Jason Alfrey, Vacuum Technology, Inc., **Freek Molkenboer**, TNO Science and Industry, the Netherlands

2:20pm **VT-TuA-1 Design and Fabrication of Ultra-High Vacuum Test System for Quantitative Determination of Hydrogen Gettering and Permeation of Various Materials***, **Ewa Ronnebro**, R. Storms, S. Suffield,* Pacific Northwest National Laboratory*; M. Boeckmann, A. Parrot, J. Alfrey,* Vacuum Technology, Inc. **INVITED**

We will discuss a recently built state-of-the-art ultra-high-vacuum (UHV) test system with sensitive detection and quantification of hydrogen uptake, solubility and diffusion in various materials. The test system's manifold is equipped with capacitance diaphragm gauges (CDG), residual gas analyzer, spinning rotor gauge, calibrated volumes, turbo pumps, scroll pumps and a leak detector. The manifold is surrounded by a bake-out oven to keep impurity levels sufficiently low. Two sample chambers are enclosed by high-temperature furnaces. The design was developed by Pacific Northwest National Laboratory (PNNL) in collaboration with Vacuum Technology Inc (VTI). This automated UHV system can be used for several studies of hydrogen-metal interactions including absorption/desorption kinetics, thermodynamics, isotherms, plateau pressures, isotope studies, gaseous impurity identification and permeation rate.

3:00pm **VT-TuA-3 Gas Partial Pressure Measurement by Remote Plasma Optical Emission Spectroscopy & Automated Analysis Using Artificial Intelligence***, **Dermot Monaghan**, J. Brindley, B. Daniel, V. Bellido-Gonzales,* Gencoa Ltd, UK

Vacuum deposition processes are being equipped with an ever-expanding array of sensors to gain more control over the process conditions. Unfortunately, this often presents the operator with too much data to be able to draw clear insights into the performance of the process. Machine learning algorithms are a powerful tool for analyzing large and complex sets of data and have been at the forefront of a revolution artificial intelligence. These techniques are ideally suited for analyzing problems encountered in vacuum processes, which are often expressed as "classification problems", i.e., identifying if a leak is present in the system or not. In particular, they can be applied to the automated analysis of vacuum processes by remote plasma optical emission spectroscopy (RPOES).

Remote plasma OES provides critical information on the state or condition of a process via measurement of residual gas partial pressure present in the chamber. RPOES is now a popular method of residual gas analysis (RGA), as it is industrially robust compared quadrupole mass spectrometry methods and operates from 0.5 mbar to 10^{-7} mbar. Whilst RGA information is important, expert knowledge is often required to be able to interpret the data, and in some cases, the spectra are too complex to extract key information using the human eye alone. This paper will present the application of a machine learning A.I. to the automated analysis of magnetron and remote plasma OES data. Examples include leak detection, organic contamination detection and the identification of organic molecules from cracking patterns.

4:40pm **VT-TuA-8 How Vacuum Controlled Venting Can Improve the Imagery of Electron Microscopy***, **Tim Collins**,* DigiVac

DigiVac was recently approached to assist a customer with vacuum control in an electron microscope. Most electron microscopes are high-vacuum instruments, as vacuum is needed to prevent arcing and to allow the electrons to travel within the instrument unimpeded. However, the specific microscopes used by this customer have no on-board vacuum control. The user chooses between Low Vacuum and High Vacuum settings depending on the makeup of the sample being observed.

The customer observed that when using the High Vacuum setting, a vacuum level within the microscope deeper than 20 Pascals (approx. 150 millitorr) caused visible degradation in the final image. They emphasized their need to precisely control the vacuum between 20 and 30 pascals for optimal imaging. We hypothesized that raising the pressure slightly, then maintaining it, would attract the negatively charged electrons causing imaging difficulty.

Our engineering team designed a comprehensive solution using our FYRA Bleed Vacuum Controller allowing ambient air (or a connected gas supply) to be drawn into the chamber as the vacuum pump evacuates it, "balancing" the vacuum level where the user specifies. The bleed valve opens and closes using feedback control based on the current chamber pressure, measured with a separate thermocouple sensor.

Our experiments with the customer's electron microscope showed obvious image degradation sub-20 Pascals with significant improvement when the vacuum level was strictly controlled between 20 and 30 Pascals. After some fine tuning with the built-in PID controller that is included with FYRA, we had a clearly defined SOP for alleviating the degradation issues when the vacuum level dipped below the required range. This type of bleed valve technology has a wide range of scientific applications not just in electron microscopy, but for any user looking to precisely control vacuum, introduce gasses during processing applications, or improve vacuum drying and molecular flow.

5:00pm **VT-TuA-9 Novel Cylindrical Hot Cathode Ionisation Gauge***, **Ricardo A.S. Silva**, N. Bundaleski, O. Teodoro,* CeFiTec - Nova School of Science and Technology, Portugal

Ionisation vacuum gauges are unexpendable devices for pressure measurement in HV, and particularly UHV and XHV. However, most of their commercial realizations (e.g. Bayard Alpert gauge) are known for their lack of accuracy, mainly due to the lack of electrodes robustness and the changes in the contributions of unwanted phenomena that occur during the operation. Among the latter , the most critical are photoelectron and ion induced electron emission from an ion collector electron stimulated desorption of ions and neutrals , as well as electron backscattering from an anode [1 3]. In the present work we report a design and realization of a new hot cathode ionisation gauge aiming the suppression of these unwanted phenomena in order to obtain increased accuracy, stability and low pressure limit. In this gauge , the primary electrons form a belt like beam, following curvilinear paths in an electrode assembly resembling a cylindrical energy analyser, and end their trajectories in a Faraday cup, located inside the inner cylinder electrode [4]. The ions created by electron impact with the gas are accelerated radially towards the ion collector, practically representing one of the electrodes of the "cylindrical energy analyser". The simulations of the operation, based on a recently developed approach [5], the construction details and the first experimental tests carried out with the first and second prototypes are presented. Details of the choice of the geometry of the Faraday cup and the inclusion of a suppressor electrode on the second prototype to inhibit secondary electron emission from the ion collector are also discussed.

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5:20pm **VT-TuA-10 High Performance Sealing In Extreme Environments***,* ***Christopher Cosgrove****,* Technetics Group

This presentation details various methods of sealing to very low leak rates in extreme environments. These environments could be very high temperatures or cryogenic temperatures or very high pressures down to UHV.

Vacuum Technology Division
Room Ballroom A - Session VT-TuP

Vacuum Technology Poster Session

VT-TuP-1 Analysis and Quantification of the Impurities in a 300mm Etch Tool Exhaust During an Oxide Etch Process with CF4 Under Plasma*, Anup Kumar Doraiswamy, C. Jennings,* Air Liquide*; N. Stafford,* air liquide*; P. Nguyen,* Air Liquide

The consumption of the etching gases, primarily perfluorocarbons, is expected to significantly increase in the near future to match the increasing demand of electronic devices. While the global warming potential (GWP) from the direct emission of these perfluorocarbons (PFCs) is known, the quantity and identity of the species generated from them in the etch chamber may not be well understood. These plasma generated species can also have high GWP, contributing to the greenhouse effect in addition to being detrimental to the air quality by affecting COX NOX levels, etc. Therefore the identification, quantification and abatement of these compounds is of increasing interest to both semiconductor manufacturers and environmental regulators. Our current study focuses on analyzing and quantifying the exhaust of a 300 mm commercial etch tool during an oxide etch process using standard etching chemistry such as CF4. In our experiments, the plasma etch tool has been supplemented with a quadrupole mass spectrometer (Q-MS) and infrared spectrophotometer (FTIR) to identify and quantify the concentration of species in the exhaust generated from the plasma etching process.

VT-TuP-2 Amorphous Carbon Thin Films: Influence of Hydrogen Contamination on the Secondary Electron Emission Properties*, Carolina Adame,* CEFITEC, NOVA School of Science and Technology, Portugal*; E. Alves, N. Barradas,* DECN and IPFN, Instituto Superior Técnico, University of Lisbon, Portugal*; N. Bundaleski,* CEFITEC, NOVA School of Science and Technology, Portugal*; P. Pinto,* CERN, Switzerland*; J. Deuermeier,* CENIMAT|i3N, NOVA School of Science and Technology and CEMOP/UNINOVA, Portugal*; Y. Delaup,* CERN, Switzerland*; I. Ferreira,* CENIMAT|i3N, NOVA School of Science and Technology and CEMOP/UNINOVA, Portugal*; H. Neupert, M. Himmerlich , S. Pfeiffer, M. Rimoldi, M. Taborelli,* CERN, Switzerland*; O. Teodoro,* CEFITEC, NOVA School of Science and Technology, Portugal

One of the major limitations for the luminosity of modern particle accelerators is the formation of electron clouds (e-clouds), which cause beam instabilities, rise in pressure and thermal load to the system. The formation of electron clouds start with seeding electrons that originate in residual gas ionization (by the beam) or photoemission (from the wall, induced by synchrotron radiation). The seeding electrons are multiplied in an avalanche process induced by electron acceleration towards the walls by the beam potential, eventually creating an e-cloud.

One strategy to reduce the formation of e-clouds, successfully applied at CERN, is coating of the accelerator walls with amorphous carbon (a-carbon), having low Secondary Electron Yield (SEY). However, in some cases the coatings may become contaminated by hydrogen during the deposition, causing SEY growth above the threshold for e-cloud formation. In this work we explore the mechanism behind the change of secondary electron emission properties of a-carbon coatings due to hydrogen contamination.

a-carbon coatings were produced on Si and quartz substrates by magnetron sputtering with different amounts of D_2 added to the Ar discharge gas, to study the influence of these contaminations on SEY and resolve it from the natural contamination by hydrogen. In addition to SEY measurements, the samples were characterized by Elastic Recoil Detection Analysis (ERDA), X-ray Photoelectron Spectroscopy (XPS) and Optical Absorption Spectroscopy (OAS), providing information about their elemental, phase composition, and electronic structure.

The relative amounts of deuterium and hydrogen from the residual gas incorporated into the a-carbon thin films was quantified by ERDA. This incorporation increased SEY, and contributed to the deposition of non-uniform films, consisting of graphitic, diamond-like and hydrocarbon phases (as revealed by XPS). The SEY and optical energy gaps (determined using Tauc plots) increase with the amount of incorporated deuterium. The latter seem to be related with the amount of the graphitic phase in the samples: samples with higher graphitic-carbon fractions have lower SEY and higher light absorption, showing that graphitic regions work as energy absorbers for both light and secondary electrons. Increase of hydrogen species in the samples reduces the graphitic content, thus increasing SEY and light transmission.

Chemical Analysis and Imaging Interfaces Focus Topic
Room 302 - Session CA+HC+LS+VT-WeM

Multiphase Interfacial Analysis and Imaging

Moderators: Andrei Kolmakov, National Institute of Standards and Technology (NIST), **Slavomir Nemsak**, Advanced Light Source, Lawrence Berkeley National Laboratory

8:00am **CA+HC+LS+VT-WeM-1 Probing the Impact of Nanoscale Defect Sites in Perovskite Photovoltaic Films with Time-Resolved Photoemission Electron Microscopy*, Keshav Dani,*** 1919-1 Tancha, Kunigami-kun, Japan **INVITED**

Hybrid perovskite photovoltaic devices have rapidly emerged as promising contenders for next generation, low-cost solar cell technology. Yet, the presence of defect states critically impacts device operation, including device efficiency and potentially long-term stability. Understanding the nature of these defects, and their role in photocarrier trapping, requires techniques that are capable of probing ultrafast photocarrier dynamics at the nanoscale.

In this talk, I will discuss the development of time-resolved photoemission electron microscopy (TR PEEM) techniques in my lab [1, 2], applied to hybrid perovskite solar materials. Thereby, we directly visualize the presence of the performance limiting nanoscale defect clusters and elucidate the role of diffusion in the charge carrier trapping process [3]. By correlating PEEM measurements with other spatially resolved microscopies, we identify different types of defects that form, and study how passivation strategies may have a varied impact on them [4]. Finally, we show that these defect can act as seeds for degradation [5].

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8:40am **CA+HC+LS+VT-WeM-3 Correlating Structure and Chemistry Using Ambient Pressure Photoemission and X-Ray Scattering*, Slavomir Nemsak,*** Lawrence Berkeley Laboratory Advanced Light Source **INVITED**

In the last two decades, Ambient Pressure X-ray Photoelectron Spectroscopy (APXPS) has established itself as a go-to technique to study heterogeneous and complex materials under reaction environments. Multimodal approaches, which correlate information from two or more complementary techniques, are currently one of the forefronts of the APXPS development [1]. In the past three years, the ALS contributed one such setup: a combined Ambient Pressure PhotoEmission and X-ray Scattering (APPEXS) instrument commissioned and operated at beamline 11.0.2 [2]. The combination of the two in-situ techniques allows correlating structural and chemical information. By using APPEXS, we observed dynamics of the exsolution process of catalyst metallic nanoparticles [3]. To expand the capabilities of APPEXS further, we introduced a new platform using arrays of patterned nanoparticles to study the evolution of catalytic systems under reaction conditions [4]. Future developments of the technique(s) will be also discussed.

References

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9:20am **CA+HC+LS+VT-WeM-5 Gating of the 2D Hole Transport in Diamond by Subsurface Charges***, E. Strelcov, **Andrei Kolmakov,*** NIST

The unique electronic, physical, and thermal properties of diamond make diamond-based FETs one of the most prospective devices for high-frequency power electronics. Transfer doping of hydrogenated diamond is a common process to form 2D conducting channels in diamond FET. The electron /hole transport of such a device is sensitively dependent on near-surface scatters including charged traps.

Here, using SEM (EBIC) and AFM Kelvin probe force (KPFM) microscopies we report on imaging of the hole transport in narrow conducting channels as a function of the density and depth of near-surface charges. We demonstrate the gating effect induced by trapped charges and discuss the methods to minimize these effects.

9:40am **CA+HC+LS+VT-WeM-6 Development of 0–D Argon Collisional Radiative Model conjoined with Optical Emission Spectroscopy between 1 mTorr to 760 Torr***, **Tag Choi**, N. Abuyazid, D. Patel,* University of Illinois at Urbana-Champaign*; D. Jacobson,* LytEn. Inc*; S. Keniley, S. Dubowsky, D. Barlaz, D. Curreli, D. Ruzic,* University of Illinois at Urbana-Champaign

Optical emission spectroscopy (OES) is a non-invasive plasma diagnostic, which can be utilized with 0-dimensional argon collisional radiative model (Ar CRM) to understand dynamics of excited and charged argon species and determine plasma parameters in the system. This work aims to study rate coefficients of excited and charged argon species, calculate their densities over time and verify the theoretical results with experimental optical spectra in a wide range of pressure regimes. The model considers various types of collisions such as electron and atom excitation/ionization, photon emission, diffusion, penning ionization, and excimer formation. A merit function is used to obtain a better correlation between the theoretical and experimental densities of the various argon species. This allows the model to get a more accurate estimate of the electron temperature and the densities. Various plasma sources are used such as a low pressure inductively coupled plasma (ICP) source, dielectric barrier discharge (DBD), and microwave discharges, to produce different types of plasmas at pressure ranges of 10 – 50 mTorr and 1 – 760 Torr. The optical emission spectra and Langmuir probe measurements are collected for verifications on a low pressure ICP source and DBD discharge. For the verification of atmospheric microwave discharge, OES data is collected for temperature calculations from Specair and the model. Different plasma sources produce different electron temperatures and densities. The ICP source, DBD and microwave discharge have electron temperatures (T_e) of 2 – 5 eV, 1 – 3 eV, and 0.4 – 0.6 eV and electron density (n_e) of 1E16 to 1E18 m^3, 1E18 to 1E21 m^3, and 1E19 to 1E22 m^3 respectively. A methane and argon gas mixture are introduced to the microwave discharge to understand how plasma parameters differ from a pure argon environment.

11:00am **CA+HC+LS+VT-WeM-10 Atomic-Scale Modeling of Bismuth and Argon Clusters Sputtering of Water/Vacuum Interfaces*, Zbigniew Postawa**, M. Kański, C. Chang, S. Hrabar,* Jagiellonian University, Poland **INVITED**

Modeling of water/vacuum interfaces should consider the high vacuum pressure of water. First, there is continuous evaporation of the liquid into the vacuum chamber, which must be considered. This phenomenon poses a significant challenge for conventional experimental techniques. Yang *et al.* presented a way to reduce the impact of this phenomenon by using a microfluidic channel [1]. This approach uses an ion beam to drill a 2-3 µm window in the channel wall, exposing the liquid flowing below. Such an arrangement allows for maintaining a low base pressure (~10^{-7} mbar) in the measuring chamber. This technique has already been used to study photochemical reactions, biofilms, and liquid-liquid interfaces by secondary ion mass spectrometry or secondary electron microscopy [2]. Recently, another approach minimizing the effect of high vacuum pressure of water that uses a graphene cell encapsulating a liquid was proposed in studies with transmission electron microscopy [3].

Recently, we have developed a new ReaxFF potential parameterization for modeling C/H/O systems designed directly for sputtering simulations [4]. This parametrization is up to 3 times faster than standard ReaxFF. New force-field allowed us to perform molecular dynamics computer simulations of water and graphene-covered water systems sputtered by bismuth and argon clusters. The mechanism of molecular emission from these two systems is investigated. The effect of the projectile size and the influence of the protecting graphene sheet on the emission process is discussed.

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Acknowledgments

The work has been supported by Polish National Science Center Grant 2019/33/B/ST4/01778 and the PLGrid Infrastructure.

11:40am **CA+HC+LS+VT-WeM-12 Finite-Elements Modeling of Solid-Electrolyte Interfaces in Through-Membranes Imaging and in-Liquid Scanning Probe Experiments***, **Alexander Tselev,*** Department of Physics & CICECO-Aveiro Institute of Materials, University of Aveiro, Portugal **INVITED**

Studies of the physicochemical processes at the interfaces between solids and electrolytes interfaces require *operando* multi-parametric measurements with chemical and electric potential sensitivity, in-depth selectivity, as well as with a high lateral resolution. A number of experimental techniques were implemented for this purpose. In this talk, we will describe applications of finite-elements (FE) modeling to elucidate and interpret microscopic imaging and measurements with liquids ranging from non-polar ones to decimole electrolyte solutions. This includes probing through graphene membranes with the use of microscopy and spectroscopy tools based on high-energy beams—X-rays and electron beams, as well as low-energy probing with the use of scanning probe techniques. Scanning probe techniques can be implemented both with probes in liquids and with probes separated from the electrolytes by membranes. We will discuss liquid-solid interface probing by the Kelvin probe force microscopy (KPFM) through graphene membranes as well as by near-field microwave microscopy through dielectric membranes. Furthermore, models for piezoresponse force microscopy and KPFM with probes immersed in electrolytes will be presented. Support of this work by the project CICECO-Aveiro Institute of Materials, financed by national funds through the FCT/MEC (Portugal) and when appropriate co-financed by FEDER under the PT2020 Partnership Agreement is acknowledged.

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